Communication of Sustainability Information and Assessment within BIM-enabled Collaborative Environment

By

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Abstract

Sustainable performance of buildings has become a major concern among construction industry professionals. However, sustainability considerations are often treated as an add-on to building design, following ad hoc processes for their implementation. As a result, the most common problem to achieve a sustainable building outcome is the absence of the right information at the right time to make critical decisions. For design team members to appreciate the requirements of multidisciplinary collaboration, there is a need for transparency and a shared understanding of the process. The aim of this study is to investigate, model, and facilitate the early stages of Building Information Modelling (BIM) enabled Sustainable Building Design (SBD) by formalising the ad hoc working relationships of the best practices in order to standardise the optimal collaboration workflows. Thus, this research strives to improve BIM maturity level for SBD, assisting in the transition from "*ad hoc*" to "*defined*", and then, to "*managed*". For this purpose, this study has adopted an abductive research approach (iterative process of induction and deduction) for theory building and testing. Four (4) stages of data collection have been conducted, which have resulted in a total of 32 semi-structured interviews with industry experts from 17 organisations. Fourteen (14) "*best practice*" case studies have been identified, and 20 incidents' narratives have been collected applying the Critical Decision Method (CMD) to examine roles and responsibilities, resources, information exchanges, interdependencies, timing and sequence of events, and critical decisions. As a result, the research has classified the critical components of SBD into a framework utilising content and thematic analyses. These have included the definition of roles and competencies that are essential for SBD along with the existing opportunities, challenges, and limitations. Then, Schedules of Services for SBD have been developed for the following stages of the RIBA Plan of Work 2013: stage 0 (Strategic Definition), stage 1 (Preparation and Brief), and stage 2 (Concept Design). The abovementioned SBD components have been coordinated explicitly into a systematic process, which follows Concurrent Engineering (CE) principles utilising

Integrated DEFinition (IDEF) structured diagramming techniques (IDEF0 and IDEF3). The results have identified the key players' roles and responsibilities, tasks (BIM Uses), BIM-based deliverables, and critical decision points for SBD. Furthermore, Green BIM Box (GBB) workflow management prototype tool has been developed to analyse communication and delivery of BIM-enabled SBD in a centralised system (Common Data Environment, CDE). GBB's system architecture for SBD process automation is demonstrated through Use Case Scenarios utilising the OMG UML (Object Management Group's Unified Modelling Language) notation. The proposed solution facilitates the implementation of BIM, Information Communication Technology (ICT), and Building Performance Analysis (BPA) software to realise the benefits of combining distributed teams' expertise holistically into a common process. Finally, the research outcomes have been validated through academic and industrial reviews that have led to the refinement of the IDEF process model and framework. It has been found that collaborative patterns are repeatable for a variety of different non-domestic building types such as education, healthcare, and offices. Therefore, the research findings support the idea that a detailed process, which follows specified communication patterns, can assist in achieving sustainability targets efficiently in terms of time, cost, and effort.

Keywords: Sustainability; Design process; Collaboration; RIBA Plan of Work; Information Communication Technology (ICT); Building Information Modelling (BIM); Building Performance Analysis (BPA); Common Data Environment (CDE); Concurrent Engineering (CE); Integrated DEFinition methods (IDEF); OMG UML (Object Management Group's Unified Modelling Language); Critical Decision Method (CMD); abductive reasoning.

Contents

List of Figures

List of Tables

List of Abbreviations

AEC/O	Architecture, Engineering, Construction and Operation
AIA	American Institute of Architects
ANSI	American National Standards Institute
ASE	Analysis-Synthesis-Evaluation
ASHRAE	American Society of Heating, Refrigerating, and Air-Conditioning Engineers
BCIS	Building Cost Information Service of RICS
BCO	British Council for Offices
BEAM	Building Environmental Assessment Method
BedZED	Beddington Zero Energy Development
BEP	BIM Execution Plan
BIM	Building Information Modelling
BPA	Building Performance Analysis
BRE	Building Research Establishment
BREEAM	Building Research Establishment Environmental Assessment Method
BS	British Standard
BSI	British Standards Institution
BSRIA	Building Services Research and Information Association
CAD	Computer-Aided Drafting (or Design)
CapEx	Capital Expenditure
CASBEE	Comprehensive Assessment System for Building Environmental Efficiency
CDE	Common Data Environment
CDM	Critical Decision Method
CE	Concurrent Engineering
CIBSE	Chartered Institution of Building Services Engineers

CIC	Construction Industry Council
CIOB	Chartered Institute Of Building
COBie	Construction Operations Building Information Exchange
CPIC	Construction Project Information Committee
CSCD	Computer Supported Collaborative Design
DEC	Display Energy Certificate
DERT	Department of Environment, Transport and the Regions
DFD	Data Flow Diagram
DPoW	Digital Plan of Work
DRM	Design Responsibility Matrix
DSM	Design Structured Matrix
DTI	Department of Trade and Industry
EIR	Employers Information Requirements
EPBD	Energy Performance of Buildings Directive
EPC	Energy Performance Certificate
FM	Facilities Management
GBB	Green BIM Box
GDCPP	Generic Design and Construction Process Protocol
GSL	Government Soft Landings
GST	General Systems Theory
HVAC	Heating, Ventilating, and Air Conditioning
ICOM	Input, Control, Output, and Mechanism
ICT	Information Communication Technology
IDEF	Integrated DEFinition
IDM	Information Delivery Manual
IES-VE	Integrated Environmental Solutions – Virtual Environment
IFC	Industry Foundation Classes
IPD	Integrated Project Delivery
ISO	International Organization for Standardization

KM	Knowledge Management
LCA	Life-Cycle Assessment
LEED	Leadership in Energy and Environmental Design
LOD	Level of Detail/Development/Design
LOI	Level of Information
MEP	Mechanical, Electrical, and Plumbing services
NASA	National Aeronautics and Space Administration
NBS	National Building Specification
NCM	National Calculation Method
OCP	Online Collaboration Platform
OMG	Object Management Group
OpEx	Operational Expenditure
PAS	Publicly Available Specification
PERT	Programme Evaluation and Review Technique
PHPP	PassivHaus (or Passive House) Planning Package
POE	Post Occupancy Evaluation
RIBA	Royal Institute of British Architects
RICS	Royal Institution of Chartered Surveyors
SAP	Standard Assessment Procedure
SBD	Sustainable Building Design
SBEM	Simplified Building Energy Model
SBS	Sick Building Syndrome
SD	Sustainable Development
SNA	Social Network Analysis
SSM	Soft Systems Methodology
UML	Unified Modelling Language
UOB	Unit Of Behaviour
WIP	Work In Progress
XML	eXtensible Markup Language

Chapter 1

Introduction

1.1. Background to the research

Sustainable performance of buildings is currently a major concern among AEC/O (Architecture, Engineering, Construction and Operation) professionals due to measures such as building legislations in addition to national and regional targets (Schlueter and Thesseling, 2009). The overall goal is to reduce the environmental impact of buildings, while enhancing human comfort and health. To address this issue, many countries and international organisations have initiated rating systems (e.g. BREEAM, LEED, Passivhaus) to assess sustainable construction (Azhar et al., 2011; Haapio and Viitaniemi, 2008). Currently, these assessment methods are used as frameworks for environmental design by building professionals, although they provide little guidance over the design process. Also, it has been argued that the design of such high performance buildings is a complex, non-linear, iterative and interactive process that requires effective collaboration between the multidisciplinary teams from the early stages in order to achieve sustainability outcomes (Bouchlaghem et al., 2005; Yang et al., 2013).

Building professionals utilise performance analysis tools extensively in order to predict and quantify aspects of sustainability from early design stages and significantly ameliorate both quality and cost during a building's life cycle (Crawley et al., 2008; Attia et al., 2009; Tudor, 2013; Smith and Tardif, 2012). As a result, Building Performance Analysis (BPA) and assessment workload becomes heavier at the early design stages compared to traditional project delivery. Additionally, timely contributions of design participants and accuracy of the information delivered are important for Sustainable Building Design (SBD) to be successful (Brahme et al., 2001). For this reason, the most significant challenge to delivering a successful sustainable building is communication and co-ordination across a multidisciplinary team (Mills and Glass, 2009; Robichaud and Anantatmula, 2010). To date, the design process often suffers from lack of collaboration between design teams of different organisations. As a result, the most common problem to achieve a sustainable outcome is the absence of appropriate information to make critical decisions (DTI, 2007b). Therefore, efficient and systematic information exchanges between designers, consultants and sub-contractors are essential to achieve design goals (Pala and Bouchlaghem, 2012). Consequently, software and hardware solutions that support communication become a necessity (Peña-Mora et al., 2000). However, efficient collaboration does not result solely from the implementation of information systems (Ahmed et al., 2016); their effective use is hindered by the fact that defined strategies, which consider organisational and project requirements, are currently missing (Bouchlaghem, 2012). Conflictingly, the complexity, amount of specialisation and individual project needs do not permit the process to be defined in a prescriptive way. The dynamically changing process of SBD, requires a highly flexible structured workflow management system (Chung et al., 2003).

Crawley and Aho (1999) have described building design as a "*top-down*" process where the original concept is worked towards detailed design, allowing coordination between parties involved. In contrast, performance assessment follows the reverse route and is a "*bottom-up*" process where environmental performance is synthesised based on characteristics and technical details of the building elements. In SBD, the bottom-up processes should inform the top-down managerial process in order to achieve assurance for a holistic sustainable outcome. This assimilation presents a significant challenge to the management of SBD processes, which is exacerbated by other factors affecting the quality of the final design, such as lack of coordination in design, unclear or missing information, and poor workmanship (Cnudde et al., 1991; Hammarlund and Josephson, 1991; Burati Jr et al., 1992; Love and Li, 2000). Despite the increasing adoption of Information Communication Technology (ICT), day-to-day communication relies mainly on face-to-face meetings, or basic media such as phone and email. This fact undermines the importance of the contribution of certain disciplines at the early stages of design by making it ad hoc despite in reality being crucial for SBD. Therefore, actors' roles within the multidisciplinary design team need to be re-defined to reflect the necessary relations between a number of diverse and interdependent tasks and activities. As the scale and scope of cooperative tasks is increasing, the shared level of responsibility for design aspects should be reflected in the use of collaborative systems, and thus, defined so as processes become more transparent and understood among the project's stakeholders. This research is intended to develop a process model for SBD, which can assist current industry practices to depart from ad hoc collaboration workflows. The following Section frames the research problem and identifies the gaps in existing knowledge.

1.2. Overview of the research domain and hypothesis

Previous attempts to integrate sustainability considerations into the building design process lack the element of sequencing of activities (Cinquemani and Prior, 2010; Bordens and Abbott, 2002; Reigeluth, 1999), and reasoning of decisions (Potts and Bruns, 1988; Lewis and Mistree, 1998). This problem is further exacerbated by the varying information needs of design disciplines (Brahme et al., 2001), which result in difficulties to make optimal design decisions. To date, organisational approaches for collaborative design (Mendler and Odell, 2000; Laseau, 2001) have resulted in generic descriptive models of the design process, such as the Royal Institute of British Architects (RIBA) Plan of Work 2013 (RIBA, 2013a; RIBA, 2013b). RIBA (2013) considers sustainability aspects in a checklist, and does not integrate them into the design process along with the core objectives.

Appropriate use of ICT could facilitate integration of sustainability in the process, but it is likely to happen *"only if the design managers employ a structured, systematic approach"* (Pala and Bouchlaghem, 2012). This approach to information management would ensure that participants acquire the right information at the right time. Centralisation of information in a Common Data Environment (CDE), *"an online place for collecting, managing and sharing information"* (BSI, 2013b), would allow high level of coordination. Online Collaboration Platforms (OCPs) (e.g. Viewpoint, Asite, Conject) facilitate a CDE for communication of project information among the project teams (Anumba et al., 2002). For SBD, the need for coordinating a larger amount of information from a wider range of participants, as supported by CDEs, increases significantly (Bouchlaghem et al., 2005; Yang et al., 2013).

"*nD modelling*" has been associated with ICT-based building design as an extension of the Building Information Model (BIM) that incorporates multi-aspects of design information required at each stage of the lifecycle of a building facility (Lee et al., 2005; Ding et al., 2014). While in theory nD modelling has been made possible by the technological advancements, in practice it has not been effectively implemented in a holistic way. Although BIM adoption, in the UK, has increased in recent years (NBS, 2015b; NBS, 2016), there is scant evidence that sustainability has been systematically considered as an integral part of the BIM collaborative process. Some BIM related frameworks are based on the international assessment rating systems (Nofera and Korkmaz, 2010; Biswas and Wang, 2008; Wong and Fan, 2012; Sinou and Kyvelou, 2006; Ghosh et al., 2011; Lützkendorf and Lorenz, 2006), while others have created tools that are integrated into BIM design software to automate performance based decision-making (Schlueter and Thesseling, 2009; Welle et al., 2011; Feng et al., 2012; Huber et al., 2011; Mahdavi et al., 2001). However, organisational aspects of BIM-enabled SBD have not been addressed sufficiently in the literature (Opoku and Ahmed, 2013). Nevertheless, literature suggests that any resources for technology implementations should be split (Wilkinson, 2005; Shelbourn et al., 2007): 40 per cent people, 40 per cent process, and 20 per cent technology. This fact is controversial since most current research on BIM has focused on technological issues instead of process and people ones. The biggest challenge that this incorporation faces is the lack of coordination among people, tools, deliverables, and information requirements (Succar, 2009; Succar et al., 2012; Ruikar et al., 2006).

Despite the various performance improvement initiatives (e.g. BIM mandate, Cabinet Office, 2011), the current business model in the construction industry remains highly fragmented. This fragmented way of working does not promote interactions between stakeholders, resulting in "*lonely*" Level 1 BIM maturity, instead of collaborative Level 2 BIM maturity (Cabinet Office, 2011). Evidently, 65% of the industry is not convinced that BIM is sufficiently standardised (NBS, 2016). There is still no comprehensive and structured process to assist professionals for planning and delivery of SBD, from the early stages, so as to harness the intellectual inputs of all building professionals' disciplines. Due to the absence of a well-defined process, the implementation of a collaborative system takes place in an ad hoc manner (Bouchlaghem, 2012). Nevertheless, the iterative nature of the design process and the complex interrelationships between disciplines, make the management of this ad hoc process difficult for the early stages.

A review of literature, as summarised in this Section, suggests a lack of a common definition for a BIM-enabled sustainable design process. SBD remains subject to interpretation, and ad hoc processes are common. As each discipline works in isolated silos, the design outcome is compromised by failing to capture and integrate their inputs in a timely fashion. Clear definition of a multidisciplinary SBD process will assist practitioners to work collaboratively and add value to the design by harnessing the intellectual inputs of the various stakeholders. As the scale and scope of cooperative tasks is increasing, the shared level of responsibility for design aspects should be reflected in the use of collaborative systems, and thus, defined for processes to become more transparent and understood among the project's stakeholders. A well-defined and mapped methodology for multidisciplinary SBD can maximise the use of technological enablers (such as BIM, ICT, and BPA), for the early stages (concept design), so as to reap the benefits gained in the context of distributed teams that are the norm in construction (Bouchlaghem, 2012).

This research argues that a structured BIM-enabled collaborative design process can improve multidisciplinary communication, and thus, assist in achieving sustainability objectives more efficiently. The research attempts to identify lessons learnt from the best practices so that it can be used to inform the design of sustainable buildings in the future. It is intended to identify the components of SBD and develop a process model, which can assist industry practices to depart from ad hoc towards defined collaboration workflows.

Therefore, this study aims to address the following research question:

"What are the critical components of BIM-enabled SBD and how are they best coordinated within a holistic process that facilitates sustainability objectives at

the early stages of design so as to achieve the most economical solution (in terms of time, cost, and effort)?"

1.3. Scope of research

Several publications have developed BIM frameworks, which include categories such as people, tools, processes, technology, and competence (DTI, 2007b; Shelbourn et al., 2007; Succar, 2009; Rekola et al, 2010; Succar et al., 2012; Chen, 2014; Succar and Kassem, 2015). Nevertheless, the framework developed by Succar (2009) has been found to be the most comprehensive. It consists of three BIM fields: (i) the policy field, (ii) the technology field, and (iii) the process field. On the other hand, sustainability considerations for building design have been extensively discussed in the literature (NASA, 2001; Vakili-Ardebili and Boussabaine, 2010; McGraw-Hill Construction, 2010). The most holistic definitions of sustainability describe it as three interdependent pillars (Brundtland, 1987; DERT, 1998; Berggren, 1999; Rodriguez, 2002; Lagerstedt, 2003): (i) environmental protection, (ii) economic stability, and (iii) social responsibility. Research suggests that environmental aspects are the most prominent for determining building performance (Shrivastava, 1995; Kibert et al., 2000; Vakili-Ardebili and Boussabaine, 2010; Opoku and Ahmed, 2013). Furthermore, it has been argued that BIM can aid sustainability in aspects that can be quantified (i.e. environmental goals) (Krygiel and Nies, 2008). Environmental design goals can be roughly categorised into two groups; the first is about human comfort and health, and the second is concerned with the impact of buildings on the planet. What environmental design strives to achieve is to find the optimum balance between the two categories so as to fulfil occupants' needs with the minimum impact on the environment. Thus, the scope of this research is to integrate the BIM framework (Succar, 2009) with SBD considerations (Rodriguez, 2002), emphasising on the process and environmental dimensions (see Figure 1.1).

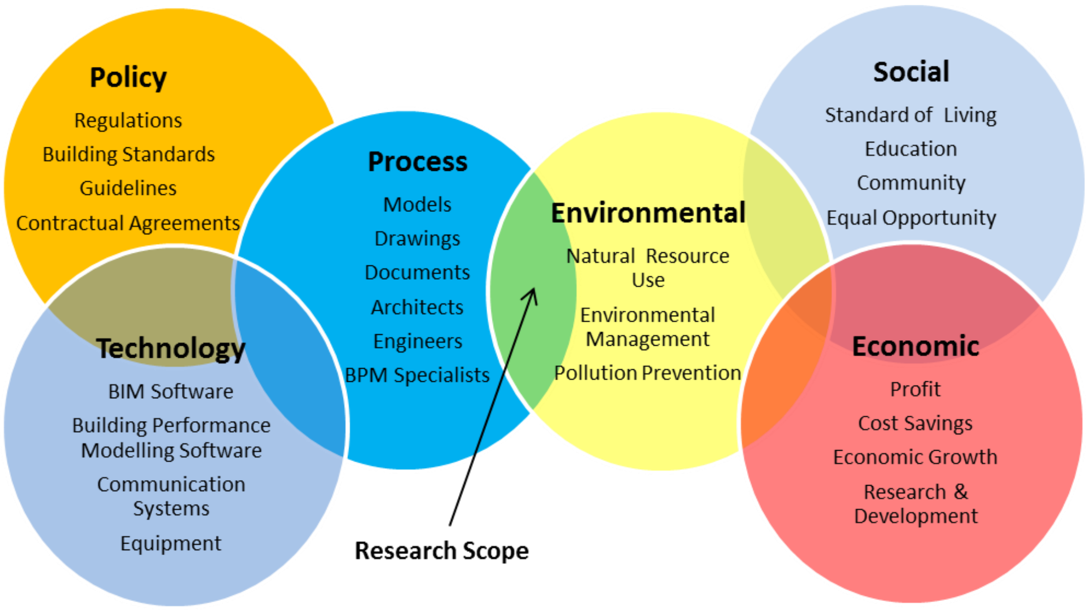


Figure 1.1 Research scope (BIM and sustainability) - frameworks adapted from Succar (2009) and Rodriguez (2002)

1.4. Aim and objectives

The aim of this research was to study, model, and facilitate the early stages of the BIM-enabled SBD process by defining the ad hoc working relationships of the best practices in order to standardise the optimal collaboration workflows.

The aim has been divided into the following objectives:

1. To explore the definition of sustainability and the existing models for the design process in order to identify the main problems in SBD management.
2. To examine the use of the state of the art technological advancements in BIM, BPA, and ICT so as to identify gaps in the existing knowledge for SBD.
3. To develop and verify a theoretical framework for BIM-enabled SBD implementation that defines the components of the process.
4. To create, evaluate, and refine a structured holistic process model for BIM-enabled SBD collaboration, which establishes the relationships between components.

5. To analyse and visualise a workflow management system that facilitates the structured process developed.

6. To assess the benefits of the research outcomes for improving the management of the SBD process and make recommendations for further research.

1.5. Research design

In order to meet the research objectives, this study adopted an abductive approach (iterative process of induction and deduction) (Dubois and Gadde, 2002; Levin-Rozalis, 2004; Reichertz, 2004; Svennevig, 2001). The implemented process was a reiteration of "*testing*" and "*explanation*" with continually checking the external validity of the research outputs (Meredith, 1993). The *"iterative theory building process"* (Drongelen, 2001) consisted of the following tasks:

1. A comprehensive literature survey to review the related books, scientific journals, and publications concerning sustainability, the nature of design, design management, modelling of the design process, and Concurrent Engineering (CE) along with BIM, BPA, and ICT.
2. Review of the structured diagramming techniques and development of a high-level process model, for SBD, based on the RIBA Plan of Work 2013.
3. Exploratory interviews with professionals (5 participants) to identify current practices of managing SBD and main problems. Moreover, the high-level process model was validated during these interviews.
4. In-depth semi-structured interviews (with 20 experts) were performed in order to develop detailed decompositions of the SBD sub-processes, based on the identified patterns. Here, 20 incidents' narratives were collected, and flowcharts of the collaboration workflows were developed. The experts were asked to identify examples of successful and unsuccessful collaboration workflows, based on the sustainability outcome. This process continued until no more information, related to the research questions, was provided by the experts (theoretical saturation/information redundancy).

5. The findings were analysed and triangulated with the literature in order to complete the framework of SBD components, and provide explanations so as to suggest improvements for SBD management, utilising the existing technological enablers.
6. Two workshops (with eight (8) academic participants) were performed to validate the research framework and concept developed. Furthermore, seven (7) in-depth interviews were performed with industry practitioners (experts in SBD). During the interviews, the process model's decompositions, and recommendations, were presented and evaluated for their accuracy and adequacy.
7. The benefits of the outputs developed are demonstrated through feedback from SBD professionals. The feedback received assisted in refining the process model and has elicited suggestions for future work.

1.6. Outline of the thesis

The thesis has been organised in eight Chapters, and a schematic guide to the thesis is illustrated in Figure 1.2.

A brief summary of each Chapter is provided below:

Chapter 1 - Introduction

This Chapter presents the background of the research and provides justifications for its importance. The aim and objectives are also presented along with the research design and guide to the thesis.

Chapter 2 - The sustainable building design process and its management

This Chapter contains the first part of the literature review. The focus of this Chapter is to provide an overview of the existing policies, definitions, and goals of SBD implementation and process, with emphasis on environmental aspects. Furthermore, this Chapter examines the managerial issues of the design process along with the existing models and frameworks used for collaboration.

Chapter 3 - BIM-enabled sustainable design and delivery

This Chapter contains the second part of the literature review. It defines the existing definitions of BIM (e.g. "Building Information Modelling" and "Building Information Management") and discusses the policy, technology, and process aspects of BIM. Moreover, the Chapter examines the synergies of BIM and sustainability, and identifies areas that affect the BIM-enabled multidisciplinary collaborative SBD implementation.

Chapter 4 - Research design and methodology

This Chapter discusses the philosophical underpinnings of this research project (epistemology and theoretical perspective), which guide the methodology (strategy, or plan of action) and justify the methods (techniques and procedures) used. The Chapter also describes the research design and process; discussing decisions that took place regarding data generation, management, and analysis as well as quality measures considered to ensure the validity and reliability of this research.

Chapter 5 - Development of BIM-enabled SBD process framework

This Chapter presents the research findings (from in-depth interviews and literature review) utilising content analysis (Elo and Kyngäs, 2008) and thematic analysis (Braun and Clarke, 2006) to identify the opportunities, challenges, and limitations for the implementation of BIM-enabled SBD utilising the existing technological enablers.

Chapter 6 - Development of SBD process model and system architecture

This Chapter contains the development of the process model for BIM-enabled SBD collaboration. The Chapter describes the coordination of the SBD components and the development of detailed decompositions based on incidents' narratives utilising the Critical Decision Method (CDM) (Klein et al., 1989). Then, it presents the development of a system's architecture for a workflow management tool for collaborative SBD process automation (i.e. Green BIM Box, GBB).

Chapter 7 - Validation of research outputs and model refinement

This Chapter establishes the trustworthiness of the research outcomes through academic and industrial reviews. First, the Chapter discusses the methods and feedback received from academic workshops and interviews with industry practitioners, experts in SBD. Then, it presents the SBD process model, amended to accommodate the recommendations made by the industrial participants.

Chapter 8 – Conclusion

This Chapter discusses the main research findings and provides reflections. In addition, the Chapter explains the limitations of the study along with recommendations for future work.

1.7. Summary

This Chapter has discussed the background of the research area and provided justifications for the significance of the problems of the domain in an attempt to demonstrate both the scientific and practical utility of the research study's achievements. Furthermore, the research aim and objectives have been presented along with the research question and methodology. Finally, the structure of the thesis has been illustrated and explained.

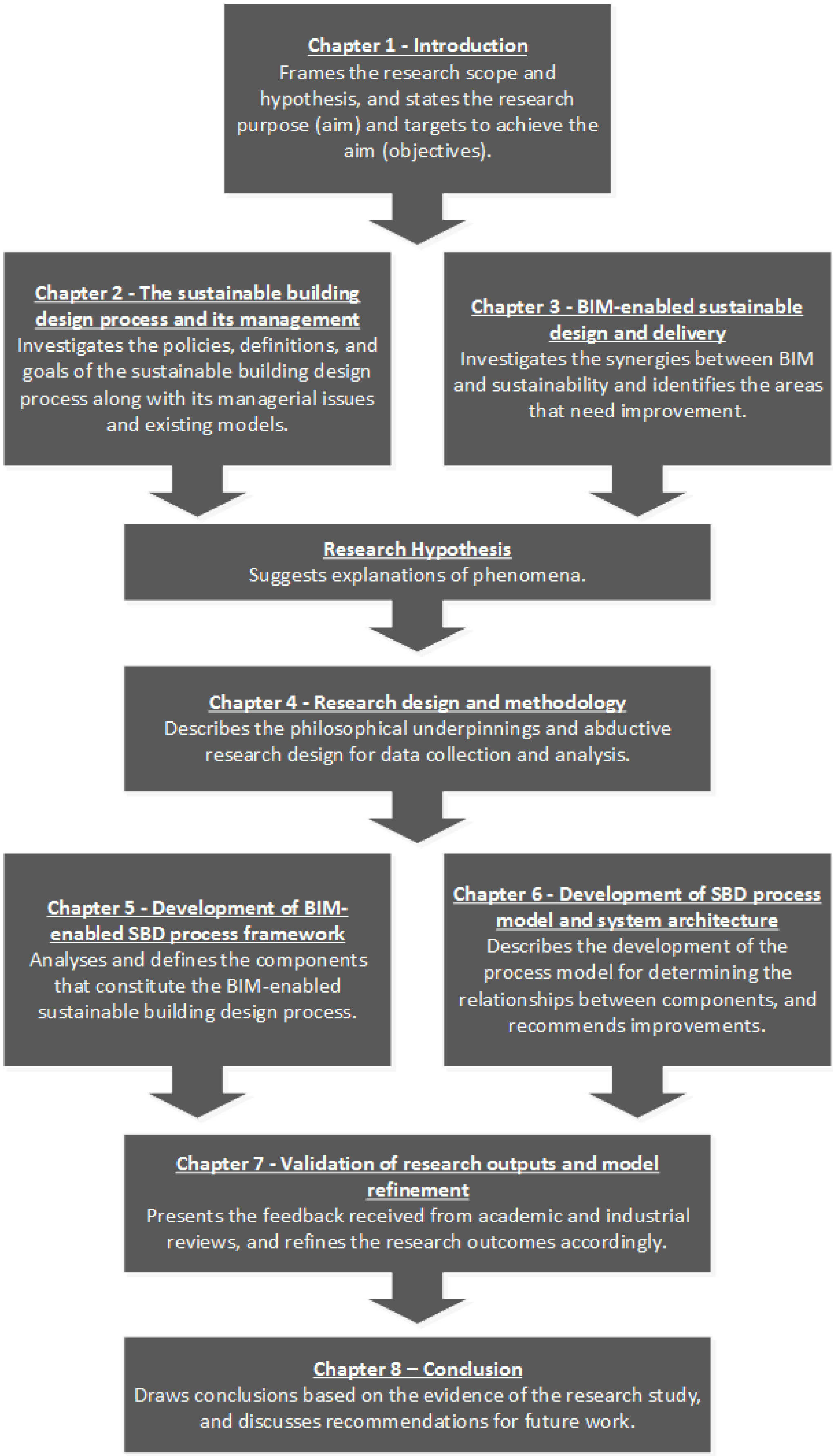


Figure 1.2 Guide to the thesis

Chapter 2

The sustainable building design process and its management

2.1. Introduction

This Chapter contains the first part of the literature review which underpins objective one, presented in Section 1.4. The focus of this Chapter is to provide an overview of the existing policies, definitions, and scope of SBD implementation and process, as well as to identify the gaps in existing knowledge. The Chapter has been divided into two main Sections. The first Section (2.2) discusses the definition of Sustainable Development (SD) and SBD goals, with emphasis on environmental aspects. The second Section (2.3), outlines the managerial issues of the design process along with the existing models and frameworks used for collaboration. Finally, Section 2.4 summarises the key topics of the Chapter.

2.2. Sustainability and the built environment

Sustainability awareness was raised in the 1960's with Rachel Carson's book *"Silent Spring"* in 1962 (Carson, 2002). The book initiated an inspired environmental movement that led to the foundation of the United States Environmental Protection Agency (EPA) in the 1970's. Sustainability has also been connected to the Green Building movement; a small group of design professionals and building occupants that realised the impacts of standard construction practices (Krygiel and Nies, 2008). Early in the 1990's the formation of the US Green Building Council (USGBC, 2016) is an important milestone to the cause. The UK Green Building Council (UKGBC, 2016), which was formed in 2007, focuses on environmental issues such as the use of water, materials and energy. More recent initiatives to improve building performance are the UK Governments' Carbon Reduction Commitment (CRC) Energy Efficiency Scheme that was introduced in 2008 as the CRC and the Energy Act 2011 (HM Government, 2011), which key provisions are the Green Deal, Energy Company

Obligation, and Energy Performance Certificate (EPC) (HM Government, 2015). Additionally, following Article 8 of the European Union (EU) Energy Efficiency Directive (2012/27/EU), which requires that member states introduce regular energy audits for large enterprises with more than 250 employees or turnover exceeding 50 million euros, the UK Government implemented the Energy Savings Opportunity Scheme (ESOS). The goal of Part L of Building Regulations is that all new dwellings are *"zero carbon"* rated by 2016, and that all new non-domestic buildings are zero carbon from 2019 (HM Government, 2016a). However, on the 10th of May 2016, the Government relinquished the amendment for the zero carbon homes initiative.

Thus, the sustainable performance of buildings has become a major concern among AEC/O professionals. The overall goal is to reduce the environmental impact of buildings while enhancing human comfort and health. To address this issue, many countries and international organisations have initiated rating systems to assess sustainable construction (Azhar, te al., 2011; Haapio and Viitaniemi, 2008). Some examples are UK's BREEAM (Building Research Establishment's Environmental Assessment Method), USA's LEED (Leadership in Energy and Environmental Design), Australia's GREEN STAR, Japan's CASBEE (Comprehensive Assessment System for Building Environmental Efficiency) and Germany's Passivhaus (Passive House Institute Darmstadt). These assessment methods are currently used as frameworks for SBD by AEC/O professionals, although they provide little guidance over the critical issues concerning sustainability during the design process. Moreover, professionals utilise BPA tools to predict and quantify aspects of sustainability from early design stages and significantly ameliorate both quality and cost during a building's life cycle. Despite the proven benefits of these tools (Ding, 2008; Gerber et al., 2012; Parasonis et al., 2012; Stumpf et al., 2009), their practice should be utilised with careful consideration of the information requirements and the expected outputs of certain types of analysis (see Chapter 3, Section 3.5.2). The following sub-Sections provide the definition and scope of sustainability for building design.

2.2.1. Definition of Sustainable Development (SD)

The definition of sustainability varies, and is dependent on the scope of knowledge, area of expertise, and social position (Vakili-Ardebili, 2005). A common definition for SD has been given by the Norwegian Prime minister Gro Harlem Brundtland and was presented in World Commission on environment and Development (WCED) on 1987. It states that (Brundtland, 1987):

> *"Sustainable development is development that meets the needs of present without compromising the ability of future generation to meet their own needs."*

The report further adds:

> *"In essence, sustainable development is a process of change in which exploitation of resources, the direction of investments, the orientation of technological development, and institutional changes are all in harmony and enhance current and future potential to meet human needs and aspiration."*

In the UK, the Department of Environment, Transport and the Regions (DETR) defines SD as (DERT, 1998):

> *"Sustainable development … is concerned with achieving economic growth, in the form of higher living standards, while protecting and where possible enhancing the environment."*

2.2.2. Dimensions of SD

The above definitions describe sustainability as three interdependent pillars; environmental protection, economic stability, and social responsibility (Lagerstedt, 2003). The University of Michigan Sustainability Assessment and Reporting Team published a report in 2002 to propose a definition of sustainability and a framework for assessment (Rodriguez, 2002). The three interlocking pillars, shown in Figure 2.1, are always interrelated but sometimes they become conflicting (Berggren, 1999).

Environmental sustainability is achieved when human activities are performed without depleting the natural resources or degrading the natural environment (Vakili-

Ardebili, 2005). It is concerned with energy consumption, biological diversity, human health and wellbeing, and life-cycle assessment. The scope of this aspect is to preserve the planet for the existing and future generations so that it can accommodate their needs. Criticism on SD is made by environmentalists who claim that the definition of SD consists of contradictory terms that have been used as an excuse to continue destroying the natural world (Dresner, 2008). Economic sustainability is about enhancing profitability based on resources, finance, labour, time, and management. It strives to achieve cost reduction through efficiency improvement in order to create added value (Vakili-Ardebili, 2005). Social responsibility is a crucial aspect of SD (Edum-Fotwe and Price, 2009), which focuses on improving the quality of life for humans. This dimension is not only concerned with the end product (e.g. building); it is a human value-driven process (Bradley and Kibert, 1998) that focuses on the systems that create and consume the product (Carpenter, 2002). It is apparent that a balance between those different aspects is crucial to achieve sustainability. Re-inventing and clarifying the SBD processes according to the current context is important and necessary for long-term sustainability.

Figure 2.1 The three pillars of sustainability (adapted from Rodriguez, 2002)

2.2.3. Impacts of buildings on SD

The building sector has direct links to various aspects of SD. On one hand it supports economic development, and human comfort and health, while on the other hand, it consumes natural resources (land, materials, energy and water) (Bourdeau et al., 1997). It has been found that building construction consumes 40% of raw stone, gravel and sand, 25% of raw timber, and 16% of water annually worldwide (Lippiatt, 1999). Several studies have focused on environmental deterioration caused by buildings (DTI, 2007a; Boussabaine and Kirkham, 2008; Shrivastava, 1995). Moreover, the energy performance of buildings is discussed in the Directive 2010/31/EU of the European Parliament and the Council (2010). It is stated that buildings account for more than 40% of global carbon dioxide (CO_2) emissions in the European Community and that this trend is constantly expanding. The suggested solution is the following:

> *"Therefore, reduction of energy consumption and the use of energy from renewable sources in the buildings sector constitute important measures needed to reduce the Union's energy dependency and greenhouse gas emissions."*

These measures are necessary in order to comply with the Kyoto Protocol (1997) to the United Nations Framework Convention on Climate Change (UNFCCC) (1992) (UN, 2014) and the UK Government's commitment to reduce gas emissions by at least 20% below 1990 levels by 2020. Furthermore, the UK Government is committed to reduce emissions by at least 80% by 2050, compared to 1990 levels, according to the Climate Change Act 2008 (HM Government, 2008). In addition, the commitments to the reduction of climate change have been reaffirmed in the 2015 United Nations Climate Change Conference (held in Paris). Boussabaine and Kirkham (2008) classify the environmental impacts of buildings into two broad categories: (i) atmospheric related and (ii) resources related. The former are reflected in problems such as the greenhouse effect and the ozone layer, and the latter refer to water pollution and natural resources scarcity.

In July 2013, the UK Government published the *"Construction 2025"* (HM Government, 2013) report that sets its long-term vision for SD of the building sector.

The report builds on the Latham (1994) and Egan (1998) reports as well as the principles of 2011 and 2012 Government's Construction Strategy reports (Cabinet Office, 2011). The reports suggest 33% reduction on initial and whole-life costs of buildings, 50% reduction in overall time to completion, 50% reduction of greenhouse gas emissions, and 50% reduction of the trade gap between export and import of construction materials. For these ambitious targets to be met, the current working practices need to be re-designed to improve the efficiency of the industry. Construction 2025 sets five key components: (i) diverse workforce, (ii) smart and innovative technologies, (iii) low-carbon and green construction exports, (iv) growth through the entire economy, and (v) clear leadership.

2.2.4. Sustainable Building Design (SBD) goals

Sustainable design principles have their routes in vernacular architecture (Krygiel and Nies, 2008). However, SBD is a dynamic evolving process defined as a function of time, experience, and innovation (Charter, 2002; Vakili-Ardebili, 2005). This fact implies that the optimal conditions for a building's life-cycle require constant examination for continuous improvement. In that aspect the concept of sustainability is linked to the quality concept through a balance between the environmental dimension and the existing conditions (Parkin, 2000). Brandon (1999) has described quality in terms of performance, energy, waste, emissions, and longevity so as to meet current and future needs. The quality of the final design is affected by factors such as lack of coordination in design, unclear or missing information, and poor workmanship (Burati Jr et al., 1992; Cnudde et al., 1991; Hammarlund and Josephson, 1991; Love and Li, 2000). The decisions made at the design stage regarding the implementation of building strategies are critical to achieve sustainable performance targets. As a result, architects and engineers are the main players in SBD development. For this reason, their roles and responsibilities need to be clearly defined and understood so as to achieve sustainability goals.

A building that resembles the function of the natural environment by producing zero waste is considered a goal of high priority (Kibert et al., 2000). This target focuses on careful exploitation of materials and resources throughout the Whole Life-Cycle (WLC) of the building. Thus, material flow consideration from "*cradle to grave*" is essential. The National Aeronautics and Space Administration (NASA) highlights the following elements as essential for sustainable design (NASA, 2001): (i) energy efficiency and water conservation; (ii) site selection to minimise environmental and transportation impact; (iii) sustainable materials; (iv) durable and efficient materials and equipment; (v) healthy environment and air quality; (vi) features to support worker productivity; (vii) design for security and safety; design for decommissioning and disposal; (viii) enhanced building operation and maintenance; and (ix) definition of objectives and verification of the level of performance.

Other authors focus on functionality (Giedion, 1967), adaptability (Glen, 1994), flexibility (Slaughter, 2001), durability and longevity (Kibert et al., 2000), health and safety (Doroudiani and Omidian, 2010; Stellman, 1998; Wildavsky, 1997), human-building interaction (Du Plessis, 2001), reliability and usability (Markeset and Kumar, 2003), disassembling (Macozoma, 2002), maintainability (Chew et al., 2004), energy efficiency (Che et al., 2010; Diakaki et al., 2008; Kneifel, 2010; Laustsen, 2008), embodied energy and embodied carbon (Hammond and Jones, 2008; Lazarus, 2004), recycling (Thompson, 1977), equipment and appliances (Menezes et al., 2012; Wood and Newborough, 2003), technology use (Emmitt and Ruikar, 2013; Ho, 2005; Newton et al., 2009), and environmental design (CIBSE, 2006a; Mourshed et al., 2003; Pelsmakers, 2011). Brandon (1999) has described quality of the sustainable outcome in terms of performance, energy, waste, emissions, and longevity.

Vakili-Ardebili and Boussabaine (2010) have acknowledged the complexity of sustainable building principles and have identified the following as the most important clusters of eco-determinants: design aspects and strategies, environmental impacts, design environmental strategies, social aspects, site analysis and economy. McGraw-Hill Construction (2010) have described the following green design and construction activities as important for practitioners: energy performance, lighting analysis, HVAC (Heating, Ventilating, and Air Conditioning) design, green building certification, cost estimating, building product material, electrical design, renewable energy, carbon emission analysis, plant selection and water use.

Performance based building design provides the means to implement a holistic sustainable design outcome. For this reason, it departs from prescriptive standards to achieve the above mentioned goals. It is concerned with fulfilling the requirements of the building relying on a flexible concept for building design, construction, and facilities management (Lee and Barrett, 2003). It is also concerned with the physical performance characteristics of a building as a whole, as well as each of its parts (Clift and Butler, 1995). Crawley and Aho (1999) have described building design (and systems design) as a top-down process where the original concept is worked towards detailed design. On the other hand, performance assessment follows the opposite route and is a bottom-up process where environmental performance is synthesised based on characteristics and technical details of the elements. It has been found that the majority of performance issues focus on the environmental aspects of sustainability (Kibert et al., 2000; Opoku and Ahmed, 2013; Vakili-Ardebili and Boussabaine, 2010). For this reason, this research has focused on the environmental aspects of SBD implementation.

2.2.5. Environmental design goals for building performance

Environmental design goals can be roughly categorised into two groups; the first is about human comfort and health, and the second is concerned with the impact of buildings on the planet. What environmental design strives to achieve is to find the optimum balance between the two categories so as to fulfil occupants' needs with the minimum impact on the environment. Several studies have focused on the importance of occupant behaviour in buildings (Andersen et al., 2009; Karjalainen, 2007; Parsons, 2002; Wei et al., 2011). These studies reveal that human comfort is subjective and that when the users of the building do not feel comfortable, they adjust the space according to their needs. This is a common reason for building design strategies failing to achieve energy performance targets. Consulting the building occupants from the early stages, in order to adapt design to their needs and appropriate control arrangements, is critical for the environmental design strategies to succeed. Thus, the SBD targets should be made explicit before concept design starts. Furthermore, they should be re-examined regularly as design progresses. This research aims to define the scope of sustainability considerations at the early stages, and align those with the tasks and responsibilities of the design team's members.

2.2.5.1. Occupant comfort and health

Since buildings are designed for people, the highest priority of SBD is to assist them accomplish their life tasks while feeling comfortable and healthy. Aspects that affect occupant comfort and health include thermal comfort, visual comfort, acoustic comfort, along with air and water quality (McMullan, 2007; Szokolay, 2008). Furthermore, comfort levels vary and depend on the activity that is performed inside the building (CIBSE, 2006).

Thermal comfort is defined as *"the condition of mind that expresses satisfaction with the thermal environment, it requires subjective evaluation"* (ASHRAE, 1997). Szokolay (2008) groups the factors that affect heat dissipation of the body into three sets: environmental (e.g. air temperature, air movement, humidity, radiation), personal (e.g. metabolic rate, clothing, state of health, acclimatisation), and contributing factors (e.g. food and drink, body shape, subcutaneous fat, age and gender). The first set is dependent on climatic data of the building's location. The other two sets (personal and contributing factors) can be investigated after engagement of the design team with the occupants of the building. Olgyay (1953) introduced the *"bioclimatic chart"* to measure thermal comfort and the *"comfort zone".* Another standard to measure comfort is the Predicted Mean Vote (PMV) (Olesen and Brager, 2004), which refers to a scale form Cold (-3) to Hot (+3). The latest most accepted method to measure thermal comfort is the Effective Temperature ET* (ET star) and its standardised method, the Standard Effective Temperature (SET) (Szokolay, 2008). In this method, isotherms are drawn on a psychrometric chart where at higher humidities the temperature tolerance is reduced, whilst in lower humidities higher temperatures are acceptable. Furthermore, the adaptive thermal comfort approach is based on the principle that "*if a change occurs such as to produce discomfort, people react in ways which tend to restore their comfort*" (Nicol and Humphreys, 2002).

Visual comfort is the main determinant of lighting requirements. The adequacy of lighting is a quantitative requirement and the suitability of lighting is a qualitative requirement (Szokolay, 2008). The former can be measured in terms of illuminance values measured in lux (lx), and the latter is a combination of at least four factors: colour appearance and colour rendering, directionality of lighting and glare. The most preferable source of lighting is natural light, or else called daylight. The availability of daylight is dependent on sky conditions; the most common sky conditions are overcast sky, clear sky or intermediate sky. Most computer simulation tools use the overcast sky conditions for its uniformity. This way they calculate the Daylight Factor (DF) on a selected working plane for the activity as a ratio between illuminance at a point indoors to the outdoor illuminance, expressed as a percentage. Moreover, the Daylight Autonomy (DA) is represented as a percentage of annual daytime hours that a given point in a space is above a specified illumination level. It is considered a part of the dynamic daylight metrics calculations (Reinhart et al., 2006; Jakubiec et al, 2011). Daylighting is also assessed in terms of beam sun lighting; this is how the shading devices are designed to allow, or prevent, direct sunlight depending on the season of the year (to allow the sun to enter during the winter and to prevent it from entering during the summer). Such design strategies are implemented in order to complement heating design strategies (for thermal comfort) as well as to avoid glare (for visual comfort). Electric lighting is used to complement natural light but careful examination is needed for the selection of lamp and luminaire since they can make a significant difference on performance. Moreover, lighting loads may cause significant addition to the thermal load (Baker and Steemers, 1996). Solar control is a challenging task for building design; the designer’s knowledge and training plays an important role to achieve the appropriate balance and ensure both human comfort, and cost savings.

As with thermal and visual comfort, there are technical properties that affect the acoustic comfort within an enclosed space. Exclusion of unwanted noise is also an important aspect of acoustic quality of a room (McMullan, 2007). Although this aspect of design is more pertinent for a concert hall or an auditorium, it is also very critical for commercial building design to enhance productivity and effectiveness of the occupants. The following conditions are important for "*good acoustics*" (Szokolay, 2008): to minimise background noise and maximise wanted sound, well-diffused sound field, prevent echoes and achieve appropriate Reverberation Time (RT) for the purpose. For this reason, the shape and size of the room play an important role, along with the room surfaces' absorption, or reflection, properties.

Sick Building Syndrome (SBS) is a term recognised by the World Health Organisation (WHO, 2016) to describe the phenomenon of people experiencing discomfort and ill health in a building when no specific illness can be identified (Burge, 2004; Redlich et al., 1997). It has been suggested that 30% of new and refurbished buildings suffer from SBS although it is more common in office buildings. The causes of discomfort have been identified as physical comfort conditions (e.g. uncomfortable temperatures, low humidity, low air movement, unsuitable lighting, excessive noise, low ventilation rates, radiation from electrical services and appliances), chemical pollutants (e.g. cigarette smoke, formaldehyde vapours, vapours from adhesives, ozone gas), and microbial (e.g. airborne micro-organisms, micro-organisms in drinking water, micro-organisms in carpets and fabrics). To avoid SBS, attention must be paid during design, installation, and maintenance of building components.

Overall, as Gestalt psychology (Koffka, 2013) discusses, *"the whole is more than the sum of its parts".* This means that psychological effects, which are subconscious, also affect the perceived experience in a building. Often attitude, or personal relationships, affect the response to the design outcome (Andersen et al., 2009; Deuble and de Dear, 2012; Parsons, 2002). The above mentioned studies have found that occupants are more tolerant towards "*green*" buildings and are more likely to adapt their behaviour accordingly. What is more, they are more likely to be satisfied despite the fact that strict comfort conditions are not met.

2.2.5.2. Use of natural resources and environmental impact

SBD strategies utilise materials and natural resources in order to fulfil the design goals discussed above, while maintaining design economy. The most preferable design strategy is the one that achieves more with less; focusing on exploiting the minimum amount of natural resources, while also minimising environmental pollution

(Hausladen et al., 2008; Hausladen, 2005). The most common resources that buildings require are materials, energy, water, and land.

Material selection is a complex issue that requires conscious consideration and management (Akintoye, 1995). It not only affects structure, form, aesthetics, cost, and internal and external environments of buildings, but also, the choice of materials plays an important role for SBD as well since it has a significant impact on the thermal, visual, and acoustic environment of the building. Environmental aspects of materials in general are concerned with where materials come from, and whether they are responsibly sourced (Glass et al., 2012; Glass, 2011). CFCs (chlorofluolocarbon), HCFCs (hydrochlorofluocarbons), HFCs (hydrofluocarbons), and halons that exist in materials contribute to the ozone layer depletion, greenhouse effect, and global warming. Moreover, material extraction and manufacture are critical for human health (e.g. asbestos, radioactivity, toxicity); toxics and volatile organic compound can negatively affect human health (Wolkoff and Nielsen, 1996). In addition, embodied carbon, or embodied energy, of materials is significant for material selection; i.e. the energy that is used to extract, transport, and process the material. There are various methods to calculate embodied carbon of construction materials such as BedZED (Beddington Zero Energy Development) (Lazarus, 2004), and the University of Bath's inventory of carbon and energy database, which lists almost 200 different materials (Hammond et al., 2011; Hammond and Jones, 2008; Lazarus, 2004). Life-Cycle Analysis, or Life-Cycle Assessment (LCA), examines the *"cradle to grave"* aspects including also variables such as ozone air depletion and air pollution, water acidification and eutropication, land use, ecotoxicity, and carcinogens. Sustainable Minds (2008-2016) have focused on LCA for product design, and have developed a framework and software. Eco-labelling is another attempt to measure sustainability of products (Ball, 2002; Halliday, 1995; Mattoo and Singh, 1994). The trade-off relationships between environmental aspects and the properties of the materials is a critical issue since thermal, and structural performance are equally important for sustainability. Thomas (2006) has created tables to compare properties of materials (e.g. structural, insulation). For example, he has compared the thermal conductivity (W/(m*K)) and thermal resistivity ((m*K)/W) of various materials (e.g.

expanded polystyrene slab, phenolic foam, cellulose fibre) to their embodied energy (kWh/m³).

Energy sources selection is equally important to material selection. The most common sources of energy for buildings are electricity, and fossil fuels (e.g. petroleum, coal, natural gas). Various energy related units exist such as Primary Energy (PE), Delivered Energy (DE), and Useful Energy (UE) (Thomas, 2006). Arguably, the preferable sources of energy for SBD are from clean energy (Kamat, 2007), that is renewable energy sources, such as hydroelectricity, solar energy, wind energy, tidal and wave power, geothermal energy, biomass energy, tidal power (Zeiher, 1996), and also technologies designed to improve energy efficiency such as Combined Heat and Power (CHP), and heat pumps. For biomass fuel, the primary source of energy is wood, and when properly managed, it can be considered renewable. Biomass energy technologies include combustion, biogas production, waste-to-energy conversion or Municipal Solid Waste (MSW), gasification and pyrolysis (in the presence or absence of oxygen), and ethanol fermentation (from high in starches and sugar food crops). Geothermal energy is heat that is stored in rocks and water deep in the earth's crust. When extracted, the heat is used to warm the building's interior or to generate electricity. Hydroelectric energy is a cleaner source of energy compared to fossil fuel and nuclear generators, used for buildings that are connected to the grid. Modern hydroelectric facilities consist of a dam to store water (e.g. from a river) at a high level; when the stored water flows downstream, it passes through turbines and generates electricity (Zeiher, 1996). Other type of facilities utilise the natural flow of rivers or waterfalls. Ocean energy (tidal and wave) utilise wind farms to generate electricity. Solar energy can be harnessed by various strategies such as passive solar heating (e.g. collected through glass surface), active solar heating (e.g. collected in air or water collectors using dark surfaces), solar cooling (e.g. shielding the building from collecting heat by utilising high reflectance surfaces), and photovoltaic energy from single solar cells, semicrystalline and polycrystalline solar cells, amorphous cells or dye-based cells. Photovoltaic technologies can be integrated into the architecture of buildings while maintaining an elegant appearance and are very promising especially with the latest advancements in nanotechnology (Kamat, 2007). Wind energy from windmills has been used in China, India, and Persia for over 2,000 years. The UK has one of the most advanced wind resources in Europe (Zeiher, 1996) developed as part of the Non-Fossil Fuel Obligation (NFFO) programme (Mitchell, 2000).

Water shortage is not a concern in the UK, in modern times, in contrast to other countries in Africa, Middle East, and China (Brown and Halweil, 1998; Falkenmark and Widstrand, 1992). Humans need water for drinking, but the largest amount is used for washing and waste disposal. For drinking water the most common sources of water are surface water (e.g. streams, rivers, lakes, and reservoirs), underground water (e.g. springs and wells), and rainwater (e.g. roofs and paved surfaces). In order for the water to be *"wholesome"* (suitable for drinking) it should be harmless to health, colourless, clear, and odourless. Water harvesting is a design strategy that is mostly used for non-consumptive purposes (e.g. garden irrigation) (Bunn, 1994). In the UK, the Rainwater Harvesting Association (UK-RHA, 2014) was formed in 2004 to enable member companies to co-operate in developing the UK market for Rainwater Harvesting (RWH) systems and to ensure compliance with the national standards such as BS-8515 (BSI, 2009). The biggest concern for RHW systems are their maintenance and management (Ward et al., 2012).

It is apparent that the trade-offs between SBD goals make its management complex and difficult due to the amount of specialisation needed. This research aims to coordinate the above mentioned sustainability considerations into a holistic process for multidisciplinary collaborative concept design implementation and delivery.

2.2.6. Sustainable building assessment methods

"*Assessment method*" is used to describe a technique that has assessment as one of its core functions, but may be accompanied by third party verification before issuing a performance rating or label (Cole, 2005). Worldwide, organisations have recognised the increasing demand for green buildings and have initiated rating systems for sustainable construction since the introduction of UK's BREEAM in 1990 (BREEAM, 2016). These include but are not limited to: Australia's (New South Wales Government) Green Star (2015), BASIX (Building Sustainability Index) and Building

Greenhouse Rating (ABGR); United States' LEED and Green Globes; Canada's BEPAC (Building Environmental Performance Assessment Criteria); Germany's DGNB (Deutsche Gesellschaft für Nachhaltiges Bauen) certification, and Passivhaus (Passive House Institute, 2015); India's IGBC (Indian Green Building Council) rating system; Japan's CASBEE (Comprehensive Assessment System for Built Environment Efficiency); Hong Kong's BEAM (Building Environmental Assessment Method) Plus (2016); Norway's EcoProfile (NatureWorks, 2016); France's ESCALE (Centre Scientific et Technique du Batiment, CSTB) (2000); and Sweden's EcoEffect (Crawley and Aho, 1999).

It has been claimed that certain rating systems can be used globally (Haapio and Viitaniemi, 2008), and the International Organization for Standardization (ISO) has published methods for universal assessment of buildings with ISO/TC (Technical Committee) 59/SC 17 (ISO, 2002), ISO 21931-1:2010 (ISO, 2010), and ISO 50001 (ISO, 2011). BRE has also released BREEAM International (New Construction and Refurbishment). Also, the European Commission is exploring options for an EU assessment framework for building sustainability assessment (World Green Building Council). However, it has been suggested that those attempts are bound to fail (Guy and Moore, 2005). Nevertheless, the scale in which the project is assessed is critical since the design strategies implemented should be sensitive to the local and regional climate (Emmanuel, 2005) as wells as community and culture (Cole, 2005; Guy, 2006). Another method of assessment is LCA; this method considers the impacts through a building's lifecycle, instead of limiting in the design and construction process. It is formulated to consider non-site aspects such as industrial products (Crawley and Aho, 1999). Other methods of assessment include benchmarks and checklists (Ministry of Defence, 2012); these focus on rules of thumb and give a very broad estimate of building performance.

In the UK, BREEAM is the leading method for holistic assessment of sustainable buildings. BREEAM is also the world's foremost environmental assessment method and rating system for buildings, with 425,000 buildings with certified BREEAM assessment ratings, and two million registered for assessment, since it was first launched in 1990. The assessment criteria categories include aspects related to energy and water use, the internal environment (health and well-being), pollution, transport, materials, waste, ecology and management processes. There are different types of rating system depending on the type of building (e.g. BREEAM New Construction, Refurbishment, and In Use) and there is also a scheme that focuses on master-planning (BREEAM Communities). Certified buildings are rated on a scale of "*Pass", "Good", "Very Good", "Excellent",* and "*Outstanding",* based on benchmarking and targets that are ahead of building regulations. Passivhaus is a fabric first approach to building design that focuses on passive design strategies to reduce the requirement of space heating and cooling while maintaining indoor air quality and comfort. BRE has been promoting this certification and has been registered with the Passivhaus Institut (Darmstadt, Germany, 1990) as an official Certifier for Passivhaus Buildings.

Although in most cases, this type of assessment is voluntary, it has been increasingly required by public agencies and other organisations (Cole, 2005; Retzlaff, 2008). That is one reason why their implementation is constantly accelerating (Nofera and Korkmaz, 2010). Their influence on building regulations is apparent; as an example, UK's Code for Sustainable Homes (CSH) will be incorporated into Part L of the Building Regulations for houses by 2016. Many prestigious awards are also been given each year to buildings that achieve high sustainability performance; those include BREEAM Awards, CIBSE (Chartered Institution of Building Services Engineers) Building Performance Award, UK Passivhaus Awards, RIBA Sustainability Award, and Sustainable Project of the Year. Furthermore, Ecobuild (UBM, 2016). Awards are taking place each year to celebrate innovation across the sustainable built environment. Other incentives for improving building performance are the UK Governments' initiatives such as the Carbon Reduction Commitment (CRC) Energy Efficiency Scheme was introduced in 2008 and the Energy Act 2011 (HM Government, 2011), which key provisions are the Green Deal, Energy Company Obligation, and EPC. Additionally, following Article 8 of the European Union (EU) Energy Efficiency Directive (2012/27/EU), which requires that member states introduce regular energy audits for large enterprises with more than 250 employees or turnover exceeding 50 million euros, the UK Government has implemented the Energy Savings Opportunity

Scheme (ESOS) (HM Government, 2016b). ESOS requires companies to have in place ISO 50001 (ISO, 2011), or to carry out ESOS audits, Green Deal assessments, or produce a Display Energy Certificate (DEC) (HM Government, 2015). Furthermore, Part L of Building Regulations that is focusing on "*Conservation of fuel and power*" is becoming more demanding by requesting all new dwellings are "*zero carbon"* rated by 2016, and that all new non-domestic buildings are zero carbon from 2019. However, these targets were abandoned in April 2016 (HM Government, 2016). Still, the EU Energy Performance of Buildings Directive (EPBD) laws remain significant drivers for reducing the energy consumption of buildings (European Commission, 2016). For buildings other than dwellings, the TER (Target Emission Rate) and BER (Building Emission Rate) can be calculated, and the EPC produced by following the National Calculation Method (NCM). This can be done by using approved simulation software (Approved Dynamic Simulation Models, DSMs), or by using the Simplified Building Energy Model (SBEM), a simplified compliance tool developed by BRE, which has a user interface called iSBEM. For dwellings, the Standard Assessment Procedure (SAP) should be followed. This can be done by using a computer program approved by BRE for SAP calculations on behalf of the Government.

While traditional design and construction focuses on cost, the paradigm towards SBD has focused on performance and quality goals (e.g. low energy consumption and waste, and reduced gas emissions) (Vanegas, 2003), and afterwards towards having a broader scope to include social and cultural aspects (Lützkendorf and Lorenz, 2006). Although most of the building assessment schemes consider similar categories to assess sustainability (e.g. innovation, integration, location, water, energy, materials, air quality, maintenance, management and emissions) (Todd et al., 2001), the criteria that are included within those categories, and the weightings, vary vastly (Retzlaff, 2008). Consequently, if different rating systems are applied to the same building, the results would be significantly different (Smith et al., 2006). For that reason, adaptations of the most influential rating systems have been developed for different countries to be relevant to their context and climate (e.g. LEED Canada and BREEAM ES). Thus, careful consideration when selecting between rating systems is essential in order to choose the one that better fits the client's and design team's vision. Although, it has been argued that there is not one that can be considered as the best for any situation (Bentivegna, 1997). Current assessment systems are constantly evolving and their complexity has increased; this evolution is necessary to maintain momentum (Fenner and Ryce, 2008), and comply with the adaptation principle of sustainability.

On one hand, the impact of rating systems is significant for promoting sustainability (Crawley and Aho, 1999). On the other hand, they have been accused of hindering innovation by limiting design options and by focusing on *"points-chasing"* (Cole, 2005). Although current rating systems provide a concise framework for the assessment of the end product of design (Biswas and Wang, 2008; Biswas et al., 2009), they are commonly utilised as a roadmap for the design process. This practice is not appropriate since these frameworks provide little guidance regarding the process of building design. Cinquemani and Prior (2010) have attempted to clarify the SBD process by mapping it against the RIBA stages, but still, the element of sequencing (Bordens and Abbott, 2002; Reigeluth, 1999), and reasoning of decisions (Lewis and Mistree, 1998; Potts and Bruns, 1988), are not examined. Brahme et al. (2001) have stressed the fact that different aspects of design are more relevant for different types of practitioners (e.g. architects, engineers), and have proposed a method to perform detailed simulation at early design stages, when certain pieces of information are not yet available. This is a common problem due to lack of mechanisms for communication between diverse groups (Lombardi and Brandon, 1997). However, this approach relies on estimation of parameters and the accuracy of the assessment's result is uncertain. This estimated result cannot be considered reliable for choosing between different design strategies that have very close difference in measurement. Design decisions need to be based on accurate sets of information that have the appropriate level of detail, provided by the responsible qualified party of the project team. Therefore, the design roles' responsibilities towards sustainability need to be made explicit before the design process commences. The definition of a detailed process for SBD can facilitate better coordination of the design participants, and their deliverables, resulting in achieving sustainability goals in the most efficient way possible in terms of time, cost, and effort involved.

2.3. SBD process management

UK industry reports have stressed the need for better construction management since the 1930s (Bossom, 1934). The most influential reports though have been the Latham (1994) and the Egan (1998). They both addressed the fragmentation issues of the construction industry. Latham defined the role of the Project Manager as having many forms, which may not be restricted by someone in the role of the Project Manager. Egan focused on the lack of innovation in the construction industry arguing that it should spread from procurement to building systems. The Avanti action research programme (DTI, 2007b) was implemented to address the Tavistock institute report (1965), which stated that: "*Architectural information is invariably inaccurate, ambiguous, and incomplete*". The programme utilised 3D CAD (Computer Aided Drafting), ICT, databases, and protocols to improve the quality of information, and thus, the predictability of outcomes. This whole life-cycle approach was supported by handbooks, toolkits, and on-site mentoring. The Wolstenholme et al. report, *"Never waste a good crisis"* (2009), has discussed sustainability and the interaction with the environment, along with the need for adoption of new business models that promote change. More recently, the Government Construction Strategy (Cabinet Office, 2011) (updated in 2012 as final) mandated fully collaborative BIM for its projects by 2016 (BIM processes and tools are discussed in Chapter 3 in detail). *"Construction 2025"* (HM Government, 2013) has described a clear vision for the UK construction industry consisting of talented and qualified people, efficient technological advanced solutions' implementation, and sustainable, low-carbon and green construction exports. The *"ICT and Automation (ICTA) Scoping Study Report"* (National Platform for the Built Environment, 2008) has stated that the success of the construction industry depends on the efficient creation and reuse of information; innovations should support this process improvement for timely collaboration that will result in a more sustainable built environment. Essentially, "*a good design process requires real engagement with key stakeholders but offers the prospects of more sustainable management and maintenance of assets, and more competitive running costs."* (HM Government, 2008).

Sebastian (2004) has categorised design management in architecture into the following categories: (i) engineering; – instrumental, considers rational problem solving mechanisms; (ii) design – methodological, integrate empirical and logical knowledge to protocols that guide the design activity; (iii) value – performance – quality measure, focus on the end product and the process to meet a set of requirements; (iv) systematic decision-making, try to optimise the decision making process; and (v) organisational – protocol approach, deal with design office management and administration of contractual relationships between parties. Admittedly, a clear cut distinction between approaches is not realistic as most managerial approaches combine the above categories to varying extend. For SBD to be successful, a holistic process that considers, and integrates, the above mentioned aspects is essential, and currently missing.

It is a common argument of various researchers that sustainability considerations should be integrated from the early stages of design (McAloone, 1998; Vakili-Ardebili, 2005; van Nes and Cramer, 1997). It is stated that the environment should be considered as early as possible, because after a certain point in the design process it is difficult to alter features that are key to environmental performance. Both environmental and economic consequences are bound to decisions made at the early stages of design at 80-90%, according to the Design Council (1997) (cited in Hon, 2004). The role of the designer is critical from the beginning to the obsolescence stages of design; this has been examined by Vakili-Ardebili (2005). However, their research does not consider how multidisciplinary collaboration affects SBD. The amount of specialisation required to achieve the complex design outcome is high, and thus, the process should be clarified and made explicit. SBD should be defined as a dynamic and evolving process, which is a function of time, experience, and innovation (Charter, 2002). Research shows that the quality of the final design is affected by factors such as lack of coordination in design, unclear or missing information, and poor workmanship (Burati et al., 1992; Cnudde et al., 1991; Hammarlund and Josephson, 1991; Love and Li, 2000). So as to address the issues mentioned above, the SBD process needs to be clearly understood, and communicated among the project team, before design commences. The need for transparency and coordination of the design process from the early stages of design is argued in the following sub-Sections. Furthermore, the existing management processes, and their limitations, are discussed in detail along with the organisational and design issues that arise during collaborative SBD implementation.

2.3.1. Design stages for environmentally responsible architecture

Environmentally responsible architecture has been discussed in Section 2.2.5 in detail. Dr John Todd (a biologist) characterises the ecological paradigm as less linear but rather better envisioned through chaos theory or by the hologram, embodying ceaseless mutual causality and interdependence (Zeiher, 1996). This statement implies that environmental design is a complex problem that can be satisfied by adopting various different approaches. For that reason, an integrated, holistic process is considered the most appropriate solution to problem solving.

Zeiher (1996) has defined the 13 categories of the SBD process, each one consisting of a number of considerations: (i) getting started: selection of the architect and project team, defining the project, defining environmental objectives (energy conservation and efficiency, direct and indirect environmental impacts, indoor air quality, resource conservation and recycling, and the economic imperative), and fundamental design solutions; (ii) working methods: construction methodologies, and computer modelling; (iii) environmental economics: life cycle cost, and grants and rebates; (iv) site selection and design: climate, topography, vegetation, wildlife, capacity and density, visual character, natural hazards, cultural context, energy and utilities, site access, and assessing existing toxins; (v) energy conservation and efficiency: insulation, and glazing; (vi) heating, cooling, and ventilation systems; (vii) lighting: daylighting, and artificial lighting; (viii) electrical equipment and appliances; (ix) indoor ecology: indoor air quality, electromagnetic fields, noise pollution, and radon; (x) water conservation: fixtures and appliances, biological sewage treatment, wastewater recycling/greywater systems, rainwater collection, and landscaping; (xi) resource conservation: working with existing buildings, reusing deconstructed materials, and selecting materials and products; (xii) waste prevention: recycling systems, and biodegradation; and (xiii) maintenance. The framework that Zeiher has developed can only be implemented loosely, since the actual process is more dynamic in nature, and design aspects are considered concurrently. The interdependencies of tasks, and the timing of decisions have not been considered sufficiently.

Mendler and Odell (2000) have arranged the stages of SBD into the following *"Key Steps":* (i) Project Definition, (ii) Team Building, (iii) Education and Goal Setting, (iv) Site Education, (v) Baseline Analysis, (vi) Design Concept, (vii) Design Optimisation, (viii) Documents and Specifications, (ix) Bidding and Construction, and (x) Post-occupancy. Although, the above definitions of SBD provide useful generic framework, they neither consider the relationships that exist between design goals of different stakeholders, nor they provide appropriate sequencing of activities to ensure that design trade-offs are considered timely during the SBD process.

2.3.1.1. Environmental design parameters

The environmental SBD process addresses the environmental design goals (e.g. occupant comfort and health, use of natural resources) that have been discussed in Section 2.2.5 in detail. Several authors have described the SBD process as a sequence of design strategies (Allen, 1995; Brown and DeKay, 2000; Krygiel and Nies, 2008; Lévy, 2011; Zeiher, 1996). Brown and Dekay (2000) have described the process as having three parts, as presented in Table 2.1. The first part shows analysis techniques that are concerned with the climate context, programme and use, form and envelope, and electric and hot water loads. The second part presents the passive design strategies that utilise the climate, and microclimate of the site, with the intention to reduce the need for resources; a few examples include daylight zones and borrowed daylight for natural lighting, direct-gain rooms, thermal storage walls and sunspaces for passive heating, and stack-effect, cross ventilation and wind catchers for natural ventilation. They have also discussed building parts, in particular, such as skin thickness, mass surface absorptance, light shelves, and external or movable insulation. The third part includes strategies that are used for supplementing passive systems such as electric light zones, rock beds, mechanical mass ventilation and mechanical space ventilation. These three parts can also be summarised as site, enclosure, and active mechanisms (Allen, 1995). Krygiel and Nies (2008) have described a similar process for design that follows four steps: (i) firstly appreciating the climate, culture, place, and building type, (ii) secondly determining building form to reduce consumption need, and then, (iii) implementing efficient building systems and apply renewable energy where possible; (iv) they have also added an additional consideration to the third part of the process for offsetting the negative impacts that the building has caused to the environment by planting trees to absorb the generated carbon. It has been inferred that a consensus exists among the various authors regarding the general considerations that take place during the early stages of SBD design.

Table 2.1 shows the information requirements for each part of the environmental SBD process. The increased amount of specialised information requires close collaboration between a variety of project participants [such as Architects, Civil, Structural, MEP (Mechanical, Electrical, and Plumbing services) and Acoustic Engineers, Client and Users] in order to address the trade-off relationships between the various design elements. Therefore, designers should appreciate the level of information that is essential to make an accurate decision timely. Considerations regarding the provider, or the source of this information, should begin before the actual design process starts (e.g. briefing, execution planning), and should continue to evolve as the SBD targets become more specific during concept, and developed design stages.

Table 2.1 Information requirements for the three-part environmental design process

A. Climate – use - topography	B. Building envelope -form	C. Mechanical services – energy sources
Location: latitude, longitude Orientation: magnetic declination Sun angle: clock time azimuth and altitude Insolation: direct and diffuse solar radiation kilowatt-hours per square meter (KWh/m^2), cloud cover (%), polar radiation diagrams Temperature: average minimum, average maximum (Celsius, °C) Rainfall/precipitation: millimetres (mm) Relative humidity: per cent (%) Wind analysis: speed in meters per second (m/s), direction (degrees) Sound: decibel (dB) levels and quality vary per room requirements, environmental noise prevention and elimination Flora and fauna: ecology on the site, living organisms Schedule: number of people, days of occupancy per month, hours a day of occupancy, type of activity per room Thermal analysis: air temperature (°C), air velocity (m/s), humidity (%), mean radiant temperature (°C)	Massing: rotation of orientation and analysis of building forms Materials: local, low carbon footprint, waste Properties: Thermal resistance (R-Value), Thermal transmittance (U-Value) Glazing: U-Value, G-Value, SHGC (Solar Heat Gain Coefficient), VLT (Visual Light Transmittance), LSG (Light to Solar Gain Ratio) Daylighting analysis: Daylight Factor (DF) percentage, Daylight Autonomy (DA) percentage, solar shading control, overshadowing Heating and cooling loads: Kilowatt-hours per square meter (KWh/m^2) Natural ventilation: CFD (Computational Fluid Dynamics) analysis, mean wind velocity (m/s), atmospheric boundary layer (height) Sound analysis: wave analysis, Initial Time Delay Gap (ITDG), Reverberation time (RT), Early Decay Time (EDT)	Water: Domestic Hot Water (DHW), hot and cold water (l/person), resistance flow, pumps, sterilisation, water harvesting, efficient equipment, greywater reuse, onsite water treatment, schedules, commission, operation and maintenance Lighting: Correlated Colour Temperature (CCT) in Kelvin (K), Colour Rendering Index (CRI), colour constancy, uniformity, diversity, luminous efficacy (lumens per watt), luminaire, lamps (photometrics), watts per square meter (W/m^2 per 100 lux loads), controls Ventilation: mechanical or hybrid, volumetric flow (m^3/s), mass flow (kg/s), fresh air ventilation requirement, ventilation rate, air quality, energy recovery, air filtration, ventilation effectiveness (ve) Heating and cooling: HVAC (Heating, Ventilation, and Air Conditioning), exergy, heat pumps, electric heating, Gas/oil/LPG (Liquid, Petroleum, Gas) fired indirect systems (boilers), Combined Heat and Power (CHP), Coefficient Of Performance (COP), latent loads Renewable systems: average daily output, energy losses

Arup's SPeAR (Sustainable Project Appraisal Routine) Assessment Tool considers 4 pillars for SBD: (i) Environment, (ii) Social, (iii) Natural Resources, and (iv) Economic. The pillars are represented as parts of the circle, which is the target that they are aiming towards. Whether the design has succeeded to achieve each sustainability aspect is shown by the proximity to the circle's centre (target). It should be noted, though, that this tool is meant to evaluate, rather than, guide the SBD process. Like the other design assessment methods (e.g. BREEAM and LEED), these approaches towards SBD should not be mistaken for design guidelines, as the structure of the collaborative SBD is not defined in these tools. Zhang et al. (2014) have suggested a prototype system to assess feasibility for sustainable construction based on quantitative assessment. Other research has focused on the influence of specific building features with regards to building performance; shape-energy performance (Parasonis et al., 2012). Heywood (2012) has described *"101 rules of thumb",* which are essentially some basic considerations that inform novice practitioners at the very early stage of design. These include the following issues: (i) working with site and location, (ii) manipulating orientation and form, (iii) low energy building envelope, (iv) internal environment, and (v) rules and strategies for different climatic regions. The above studies have stressed the importance of early design decisions to the final building's performance. Passive design strategies that are implemented during early concept design (e.g. building massing and orientation, location on site) have been found to have a significant effect on the resulting energy performance of a building. A structured process for SBD can guide the project team so as not to miss opportunities to optimise environmental performance.

2.3.1.2. Passive and active design strategies

Brown and Dekay (2000) have defined an entirely passive system as one that uses no auxiliary energy for fans, pumps, or to produce heating or cooling, while active systems are more mechanical in nature. Passive design strategies utilise the architectural elements to modify the building's internal climate and reduce thermal, cooling and lighting loads. The selection and implementation of passive strategies are dependent on a number of climatic elements. Allen (2005) has described the following: (i) position of the sun and solar radiation on the site, (ii) night sky radiation,

(iii) weather, (iv) precipitation, (v) microclimate, (vi) daylighting, (vii) photosynthesis, (viii) geology, (ix) biological factors, and (x) other factors caused by people (such as pollution with smokes, gases, dust, or chemical participles and noise from traffic, industrial processes). The properties of the selected building components should address these conditions in order to achieve environmental goals.

Thus, BPA software tools (discussed in Chapter 3 in detail), calculate the physical performance of a building based on set properties of materials that deal with radiation (reflectance, absorptance, emittance), conduction (thermal resistance, emissivity, thermal bridges), convection, thermal capacity, water vapour (temperature dew point), airtightness, and thermal sensation. Structural support, protection from water, and fire control should also be considered simultaneously during passive design. These decisions are based upon how much heating, cooling and lighting requirements can be satisfied by passive architectural systems. Then, the most efficient active systems that can relegate the remaining loads to achieve the comfort targets requirements, are selected. The aim of passive design is to ensure that the design solution uses as little energy as possible, irrespective of where that energy comes from (Heywood, 2012).

Finding the optimal balance between active and passive design systems presents a big challenge for environmental design. Ternoey et al. (1985) have described the range of possible solutions as two extremes, the climate-adapted and the climate-rejecting building, and their midpoint, the combination of both technologies. The climate adapted buildings are bounded by the limits of penetration of light, heat, or air, dictating the architectural form to be narrow and extended, resulting in a high surface-to-volume ratio. The midpoint solution uses buffers, like an atrium, to reduce the use of mechanical support on the building. The other extreme, the climate-rejecting building, appeared in the 1950's with the fully air-conditioned buildings. These buildings have changed the perception of humans regarding the control of their living environment leading in requirements of comfort-zone range temperatures that could be characterised as artificial and unrealistic. The use of internal environmental-control strategies has eliminated the trade-off between the need to open the building to positive climatic resources and the need to protect the building against extreme cold and heat. Currently, awareness has arisen regarding the negative impacts of overusing this approach on both human health and the natural environment; not only it has resulted in the SBS, but it has also caused a heavy load of CO_2 emissions, as discussed in Section 2.2 of this Chapter. However, in certain cases, when the inside environment needs to maintain strict conditions, this approach cannot be avoided (e.g. hospitals, high density rooms).

2.3.1.3. The impact of building technology

As discussed in the above Section, the climate-adapted buildings are based on the application of vernacular architecture principles and techniques for natural daylighting, natural ventilation, and passive solar heating and cooling. The contemporary availability of new materials and technologies is augmenting the effectiveness of those techniques to a point that was not possible in the past. These strategies in synergy can make the zero carbon emission target possible. Pelsmakers (2011) has provided an overview of low and zero carbon technologies decision-making matrices for heating, cooling and electricity describing prioritisation of design objectives and feasibility of design strategies. These matrices may be useful for novice practitioners to assist their decision-making process at the early stages of design. Clark (2013) has provided guidance on how to reduce energy consumption and carbon footprint of buildings by quantifying operating, embodied, and transport CO_2 emissions. He has aligned this discussion with the EPC assessment and BREEAM rating system, giving useful considerations for the design development. Moreover, Clements-Croome (2013) has defined the new technologies for SBD as *"intelligent buildings".* These buildings have the capabilities to respond to the occupants' needs by mainly relying on automation of mechanical and electrical systems, smart materials, and controls, and thus, resulting in lowering energy use and cost, while promoting the well-being of the occupants . These results are achieved by integrated multidisciplinary teams that follow efficient collaborative working processes. Nevertheless, the delivery of sustainability information, during collaborative SBD implementation, has not been sufficiently addressed in the literature.

2.3.2. The design synthesis

Creativity has been exposed for its complexity (Koestler, 1964); this is why it is impossible to find a single definition for this abstract notion (Goldschmidt, 2014). Apart from this fact, different people probably design in different ways (Lawson, 2006). Thus, most research focuses on the study of creative phenomena; that is cognitive processes rather than organisational approaches. The two principle themes that have been identified in the *"Design Studies"* journal are the terms *"design process"* and *"design cognition"* showing the importance of understanding how designers think, distinguishing the good practices from the less accomplished, and identifying what those patterns are that distinguish the experts from the novice designers (Chai and Xiao, 2012). Koestler (1964) has examined patterns that concern practical matters, many of them social or environmental. Ching (2010) has focused mainly on aesthetic issues and functional relationships that can be used to govern the form of the built environment, such as adding or subtracting from basic forms, emphasising horizontal or vertical elements, using symmetries or systems of proportion, and following grids or radial patterns. Laseau (2001) has described the design thinking process as *"graphic thinking",* which is a very strong tradition for communicating in architecture. He has defined graphic thinking as a means for effectively communicating, and has presented practical methods to achieve that.

2.3.2.1. Iterative nature of design

Cornick (1991) has described the iterative nature of design as consisting of the following possibilities: either conjecture, refutation, and iteration or analysis, synthesis, evaluation, and iteration. Hassan (1996) has stressed the importance of aiding tools to manage this iterative, complex process taking into account that deficiencies, in the design process, happen due to lack of communication, not technological factors. Newton (1995) has emphasised the fact that manipulation of information flows through successive stages of design is the key to design management.

The iterative nature of design makes its management challenging; the key factors of influence have been identified as information transfer and communication (Hassan, 1996). Costa and Sobek (2003) have defined the following as reasons for iterations in design: rework, design, and behavioural. The ideal design management process has been described as one that eliminates unnecessary rework, and negative behavioural characteristics (although those are more difficult to predict and prevent). The reasons for the design iterations are either a natural part of the design evolution, like trial and error, or they are the result of the changing requirements and circumstances during design (Pahl and Beitz, 1988). Thus, the aim of an efficient SBD process is to enable the trial and error iterations of design optimisation, while eliminating the ones that are caused due to lack of proper coordination. Hassan (1996) has also stressed the importance of defining the acceptance criteria before the analysis of the design takes place, while re-examining the acceptance criteria after the design synthesis and evaluation happens. Along with that, consistent communication is essential throughout the iterative design process. A structured process can facilitate efficient SBD optimisation by defining the critical decisions' scope and timing for better team alignment.

It has been argued that faster iterations can be achieved by implementing (Smith and Eppinger, 1997): (i) computer aided design systems, which accelerate design tasks; (ii) engineering analysis tools, which reduce the need for time consuming test cycles; (iii) information systems involving database management and networking software, which facilitates rapid exchange of technical information among individuals on the design team; and (iv) also removing extraneous activities from the iterative process. Furthermore, fewer iterations could be achieved by: (i) improved coordination of individuals whose work depends on each other; (i) co-location of team members responsible for tightly coupled activities for faster exchange of information and conflict resolution; (ii) minimisation of team size; (iii) proper specification of interfaces; and (iv) use of engineering models capable of predicting performance along with multiple dimensions, eliminating the need for separate analysis. This research aims to define the SBD process explicitly so as to improve the project team's coordination towards a common goal. Furthermore, the developed process can be utilised in a computerised system to accelerate workflow management of repeatable collaborative design tasks.

Cader (2008) has claimed that *"Innovation Is Iteration";* and strategic planning of the design process can enhance the implementation of construction innovations (Slaughter, 1998). However, the key problem with innovation in the construction industry is the organisation of the process (Atkin et al., 1999). To date, organisational aspects of SBD are considered as add-ons to the design process and still remain generic and ad hoc. Harty (2008) has discussed innovation in construction as a system that contains transformations of practices, processes, systems, and technologies. This study presents an innovative way for the implementation of SBD by coordinating processes, and technologies into a holistic framework and model.

2.3.2.2. Paradigm change for SBD

The *"traditional design process"* implementation consists of a serial collection of discrete tasks performed by little interaction between team members. In contrast, what the SBD process suggests is a collaborative effort to integrate the various design strategies between disciplines (Fazlic, 2013) in order to address design values and criteria (Becker, 2008). Although, this is the recommendation of every design assessment tool (BREEAM, LEED etc.) and guide (Sinclair, 2013), to this date, there is no structured approach to guide collaborative SBD. As the complexity of the design process has increased significantly, balancing trade-off relationships between design goals becomes even more essential. Despite the fact that the design targets have changed, processes for its implementation remain the same. Therefore, the design process needs to be redefined to accommodate the emergent needs.

Due to the amount of analysis required from the beginning of the process, SBD is front-loaded; the work comes at the beginning, and the rewards come later (Zeiher, 1996). For this reason, allowing time to consider and weight the environmental issues at the early stages, is crucial throughout planning. BIM processes align with this practice and can assist the implementation of SBD through the integration of reliable multi-disciplinary information (BIM processes and technology are discussed in detail in Chapter 3). This shift, like any other innovative idea, process, or technology follows an evolutionary sequence of events, between the origin of a general concept to the adoption from the general majority. This concept is described by Diffusion Theory

(Ternoey et al., 1985). For SBD, the greater demands by clients are performance, quality, economy, and time (Hassan, 1996). As the design goals have changed, and become more complex, the design process must evolve along with it. The SBD goals and strategies should be considered concurrently as design progresses, supported by expert knowledge, along with accurate and reliable information so as to make informed decisions.

2.3.3. Definitions of the design process

Pahl and Beitz (1988) have defined designing as the optimisation of given objectives within conflicting constraints. It has been argued that requirements change over time, so that a given solution can only be optimised for a particular set of circumstances. For that reason, the design process calls for close collaboration with people of different disciplines. A good flow of information is essential, and must be encouraged and maintained by proper organisation (Hassan, 1996). This way, design optimisation occurs through decision-making based on the latest updated version of design information.

Hassan (1996) defines building design as:

> *"a process which maps an explicit set of Client's and end user's requirements to produce, based on knowledge and experience, a set of documents that describe and justify a project which would satisfy these requirements plus other statutory and implicit requirements imposed by the domain and/or the environment".*

Moreover, Vakili-Ardebili (2005) discusses:

> *"In the case of building design, the process of design is a dynamic mechanism prone to improvement and can be assumed that the design stage is an evolutionary system and the level of progress and development compared with former experiences are established in the early stages of building design through employed strategies and innovations".*

Thus, for SBD, sustainability aspirations, objectives, and compliance requirements should be made clear before design starts. Nevertheless, the SBD process should maintain an amount of flexibility and openness to accommodate innovations.

2.3.3.1. Prescriptive and descriptive design models

The Design Methods movement initiated in Britain during the 1960's and its members shared the same conviction that design is not based solely on experience and intuition but should be thoroughly modified by a more systematic, scientific process that could be prescribed (Goldschmidt, 2014). This has been the first attempt to structure the design process. Most of the models that they developed, during that period, have been flowcharts (Hubka, 2013) especially the Analysis-Synthesis-Evaluation (ASE) model of the design process, proposed by Asimow (1962), has been widely accepted. The ASE model was based on the paradigm of problem solving as information processing, the same paradigm that founded cognitive science and artificial intelligence. The spiral metaphor from abstract to concrete solution has also been used to depict the iterative nature of design (Watts, 1966). Christopher Alexander (1964) proposed a prescriptive method that the designer had to follow rigid predetermined steps opposite to the creative thinking paradigm. However, this model has been found to be inefficient, and researchers proposed a new paradigm of descriptive design models. It has been argued that descriptive design models of actual design behaviour are essential to progress understanding and thinking as it occurs in real life (Goldschmidt, 2014). As a result, a partnership between designer and computer is created (Kalay et al., 1987). This way, design is facilitated but not restricted to the norm solutions, and thus, the design team is able to achieve innovative solutions in building design. This research adopts the descriptive paradigm for SBD process mapping striving not to limit design creativity.

The cognitive design process is described by Gupta and Murphy (1980) as consisting of three phases (cited in Hassan, 1996): (i) Exploratory phase, (ii) Transforming phase, and (iii) Convergence phase. The Exploratory phase is based on the information provided in the brief. During this phase, the designer aims to gain sufficient understanding of the problem. In Transformation phase, the creative process begins where the designer, based on experience and talent proposes alternative solutions to the problem. During the Convergence stage, the designer evaluates the feasibility and applicability of the proposed solutions and attempts to reach a decision about an optimal choice. Various researchers have followed a similar approach, focusing on the thought process of the designer (Austin et al., 2001; Evans et al., 1982; Jones, 1992; Lawson, 2006; Steele et al., 1999). Nonetheless, the cognitive process of design evolution could be considered subjective and different between individuals.

The organisational design process has been described by Laseau (2001) as *"architectural practice"* involving the following steps: (i) building programme, (ii) schematic design, (iii) preliminary design, (iv) design development, (v) contract documents, (vi) shop drawings, and (vii) construction. Within each of these steps he has suggested a linear five-step process model that consisted of problem definition, developing alternatives, evaluation, selection and communication. Yet, this generic descriptive model of the design process can only be implemented loosely as a framework, which focuses on organisational and contractual arrangements. Several researchers have adopted this kind of approach to mapping the design process (Ahuja and Nandakumar, 1985; Edel, 1967).

Steele (2000) has categorised the structured methods of the *"Design Movement"* into Architectural, Engineering, Descriptive, Prescriptive, and Consensus. Whereas, he has concluded that most models are based on a mixture of both elements. Thus, he has defined the Consensus models as:

> *"a representation of the kinds of design activities involved in design, while simultaneously outlining the actual design phases which make up the process itself, i.e. It combines the characteristics of both descriptive and prescriptive models into a single entity."*

This way the model does not restrict the designers' way of working. Hubka's (1980) and Cross's (1992) models have also provided a hybrid representation of the iterative design process taken by the expert designer (cited in Steele, 2000). The SBD process model, developed in this research, combines both descriptive elements (design tasks) and prescriptive rules (decision-making points), and thus, it can be considered a "*Consensus*" method.

2.3.3.2. Modelling the conceptual stage

It has been argued that the conceptual design stage is about *"problem finding"* and less about *"problem solving"* (Sebastian, 2007). However, if the design goals are not set from the start, it is likely for design team members to work towards conflicting goals. This statement, can be interpreted in a sense that the design process cannot be managed in a restrictive way (offering prescriptive solutions without any flexibility). Therefore, the analysis of a design problem is fundamental to the process, as practical design problems are variable, idiosyncratic and difficult to understand (Laseau, 2001). It has been argued that the phase of design that is considered the most interesting part of the process is the preliminary one because the problems are still ill-defined (Simon, 1977). Dorst and Cross (2001) have suggested that the cognitive process of clarification is not a sequential one, but various considerations occur in parallel. The designer first perceives an interpretation of the problem, then frames it, and reframes it again (Schön, 1984), in an iterative manner. This is the time of experimentation, comparison of alternative solutions, questioning, and evaluation, until achieving a coherent and justifiable proposal (Goldschmidt, 2014).

Steele (2000) has acknowledged that *"the major difficulty in attempting to describe rationally the process of conceptual design lies within the very nature of this intuitive, creative, innovative, heuristic, cognitive, and inspiration driven stage of the design".* In fact, those characteristics increase the complexity to make the tacit knowledge of the design industry professionals, explicit. The elements of creativity and cognitive information processing make the conceptual design stage the most difficult portion of the design process to automate (Newsome et al., 1989). For SBD, the complexity is increased because additional design criteria are introduced in the system. Indeed, the scope of the concept design remains to explore the numerous existing solutions to a problem until the best design solution arises (Chakrabarti and Bligh, 1994). Steele (2000) has concluded that there is no universal term for concept design. Nevertheless, a process that enables the transparency of the collaborative workflows, can facilitate the development of a common definition between stakeholders in order to reduce uncertainty.

2.3.3.3. Systems approach to collaborative building design

Organisation theory has found a framework in systems theory (Von Bertalanffy, 1969; Walker, 2007). General Systems Theory (GST) originated in biological sciences but its applicability has been recognised to be relevant to business organisations (see also Section 4.6). Thus, it has been usefully applied to organisation problems in industries other than the construction industry (Walker, 2007). The systems approach stresses the contribution of the interrelationships of the parts of the system and the system's adaptation to its environment in achieving its objective. Peter Morris (1972) has supported the systems approach in that he found that organisation theory could be used to describe and explain the nature of management process of construction projects (cited in Walker, 2007). Systems thinking is a method to enhance learning in complex systems and is fundamentally interdisciplinary (Erdogan et al., 2008).

The definition of the system is given by Ackoff (1960) as:

> *"An entity, conceptual or physical, which consists of interdependent parts. Each of a system's elements is connected to every other element, directly or indirectly, and no sub-set of elements is unrelated to any sub-set."*

There is a distinction between "*closed*" and "*open*" systems. The former (i.e. closed) remains unresponsive to the occurrences that happen outside (e.g. machines), while the latter (i.e. open) adapts to events and occurrences that take place outside of it. The open system has a permeable boundary and there is an import and export between an open system and its environment (Walker, 2007). Thus, it is dynamic and adapts to its environment by changing its structure and processes. Therefore, construction, like every business organisation, is an open system. An open system requires inputs from its environment, which then are been processed and transformed to produce outputs back to its environment (Jennings and Wattam, 1998). Checkland (2000) has argued that GST is not appropriate for addressing managerial "*messy problems*", and has suggested a Soft Systems Methodology (SSM) instead. Although he has also admitted that there is no clear distinction between *"hard"* (well-defined and technological), and "*soft*" (fuzzy ill-defined) problems (Checkland, 2000). Nevertheless, for performance based design that addresses quantifiable sustainability objectives, a "*systems engineering*" process can be considered appropriate for its implementation.

Cleland and King (1983) have drawn upon systems thinking (cited in Walker, 2007). Their work emphasises the concepts of interdependence, complexity, change and their representation of projects, or other organisation forms, as systems linking concepts or processes at three levels of abstraction. Walker (2007) has drawn heavily upon the work of Cleland and King (1983), and produced an innovative approach for the construction industry. He has argued that, without a structured approach, the management theory does not contribute to the effectiveness of the management of projects in industry. He has noted that the project management process functions should focus on the following issues: (i) identifying, communicating and adapting the system's objectives, (ii) ensuring the parts of the system are working effectively, (iii) ensuring the appropriate connections are established between the parts, (iv) activating the system so that the connections that have been established work effectively, and (v) relating the total system to its environment and adapting the system as required in response to changes in the environment. Functional resources analysis, or requirements analysis, is also highly significant despite not been in itself the basis upon which the organisation competes within the market (Jennings and Wattam, 1998). Identifying the stakeholders within a specific system, along with their different perceptions and viewpoints, is essential in the requirements engineering process (Sharp et al., 1999).

This research has followed a systemic approach in order to develop a structured process for collaborative SBD implementation and delivery. It is argued that for the sustainability goals to be achieved, the SBD process components (human and technological resources) need to perform at their best, while properly coordinated. The developed system is considered to be open, so as to address the flexibility needed to be able to adapt to outside events. Nevertheless, since certain aspects of environmental design can be quantified, its effectiveness is assessed towards specified metrics and benchmarks. It is considered, that this practice offers better team alignment.

2.3.3.4. Existing design models for construction

Pryke (2012) has divided the modelling of design into three groups: (i) Tasks Dependency (e.g. critical path analysis), (ii) Structural Analysis (e.g. use of management structures), and (iii) Process Mapping (e.g. cognitive mapping). Gebala and Eppinger (1991) have reviewed the common models used for representing the design procedures as the following: Directed Graphs, Programme Evaluation and Review Technique (PERT), Structured Analysis and Design Technique (SADT), and Matrices (e.g. Design Structured Matrix, DSM). DSM and PERT diagrams are suitable for deterministic activities that are either sequential or parallel but have been found to be problematic for mapping the iterative nature of the building design process (Hassan, 1996). Moreover, the iterations required in reaching final, workable designs, particularly where complex and specialist services are concerned, are ignored (Pryke, 2012). Process mapping methods are discussed in Chapter 4 in detail.

The Generic Design and Construction Process Protocol (GDCPP) has defined the complete design process (Aouad et al., 1998; Cooper et al., 2008; Kagioglou et al., 2000). The GDCPP model has not only described the physical stages of the process, but has also addressed the management of design. The *"Approval Gates"* that must be signed off before the beginning of each stage, enable to evaluate the design output, and this way, they facilitate a more efficient control of the process (Steele, 2000). Freezing the design between stages is considered to improve communication and coordination between project participants through the design stages (Sheath et al., 1996). Nevertheless, Winch and Carr (2001) have highlighted the importance of understanding the existing processes first, before forming the future processes. Another critical issue that they have discussed is the need to establish the good practices in terms of resolution of the design process, along with the production, and full definition, of the information flows that are required.

The systematic approach to concept design has been criticized by those who believe that design is an intuitive process (Minneman, 1991). This claim may be relevant for a cognitive design process, but not for an organisational and collaborative structured process, implemented in this research. Winch and Carr (2001) have advised that differences between individual projects, even in the retail sector, meant that an industry-wide generic process protocol was unlikely to be viable. However, a descriptive process that does not hinder innovation, may address this issue.

2.3.3.5. Concurrent Engineering (CE)

CE has mainly been implemented in manufacturing engineering for the development of products by implementing tasks such as the planning of the process, and quality of the outcome. CE is defined by the Institute for Defence Analysis as *"a systematic approach to the integrated, concurrent design of products and their related processes including manufacture and support"* (Hassan, 1996). The main characteristics of CE are the following (Dorf and Kusiak, 1994): (i) The cooperation in multi-disciplinary teams while they simultaneously complete the development of a new product, thus, the parallel completion of tasks is executed quicker compared to the sequential implementation of tasks; (ii) The use of sophisticated electronic tools for drawing's production; (iii) The application of rules to facilitate manufacture, assembly, and inspection; (iv) Provision of convenient spaces for meetings with facilities to maximise design team's interaction; (v) Change of the paradigm from pyramid structure to multi-disciplinary approach; (vi) The customer's viewpoint is also a consideration that is made from the start of the design process of the product; (vii) Continuous assessment of the cost is made in every decision and alternatives are parts of the process; (viii) Capturing lessons learn from mistakes are monitored and are fed to future products; and (ix) Participation of everyone at every stage.

The characteristics of a CE process resemble to the construction industry design implementation one. Thus, there has been a move towards CE processes for construction projects (Anumba et al., 2002; Anumba and Evbuomwan, 1997; Betts and Wood-Harper, 1994; De la Garza et al., 1994; Evbuomwan and Anumba, 1998; Gunasekaran and Love, 1998; Huovila et al., 1997; Kamara et al., 2000; Love and Gunasekaran, 1997; Peña-Mora et al., 2000). The aforementioned studies, along with more recent ones that have utilised BIM (Mignone et al., 2016), argue that standardising repeatable process can lead to high-value collaborative tasks. This approach has also been referred to as *"collaboration engineering"* (De Vreede and Briggs, 2005). The DSM (Eppinger and Browning, 2012) approach follows the principles of CE. DSM has also been implemented widely as a method for CE for structuring the design and construction process (Austin et al., 2000; Choo et al., 2004; Pektaş and Pultar, 2006; Yassine and Braha, 2003). However, this process is better suited for deterministic and closed systems. The SBD process is an open system, which is dynamic. Therefore, it requires more flexibility and adaptability. For this reason, this research has adopted a CE approach so as to standardise SBD management. The developed process can be used to guide the execution of repeatable SBD tasks, provide continuous assessment towards sustainability criteria, and assist into moving towards a hub centric solution for sustainability information exchanges. Furthermore, it can be used to automate, and accelerate, workflow management during concept design.

2.3.3.6. RIBA Plan of Work: The UK industry standard for design management

In the UK, the RIBA Plan of Work follows a descriptive approach for design process management. The RIBA Plan of Work, which was originally published in 1964, has been widely accepted as a standard method of operation (Cooper et al., 2008). It divides the design process into stages (e.g. briefing, design, construction, operation). Each stage consists of design tasks, assigned to design roles. Due to its popularity and the familiarity of building professionals with it, the RIBA design process (2013) has been reviewed (stage 0 "*Strategic Definition*" to stage 4 "*Technical Design*"); although the main focus of this study is on the early stages. Thus, the outcomes of this research have been aligned with the first three stages of the RIBA Plan of Work 2013: (i) 0: Strategic Definition, (ii) 1: Preparation and Brief, (iii) 2: Concept Design. The evolution of the RIBA Plan of Work (1964-2013) is shown in Table 2.2.

Table 2.2 RIBA Plan of Work evolution milestones (RIBA, 2007; RIBA, 2011; RIBA, 2012; RIBA, 2013; Cooper et al., 2008)

Versions	**RIBA Plan of Work (from 1964 to 1997)**	**RIBA Plan of Work 2007**	**Green Overlay to the RIBA Outline Plan of Work (2011)**	**BIM Overlay to the RIBA Outline Plan of Work (2012)**	**RIBA Plan of Work 2013**
Stakeholders roles	Role of the Architect as Design Leader coordinating the various designers			Introduces the term Integrated Collaborating Team and the BIM Model Manager	Introduces new roles in the Collaborative Project Team
Sustainability in design	Does not mention sustainability objectives		Introduces Sustainability Aspirations, Environmental Strategy and Sustainable Assessment	Integrated with Green Overlay	Sustainability Checkpoints
Information definition	In form of documents			Introduces BIM Data Drops, Integrated Project Delivery, Interoperability	Information Exchanges, UK Government Information Exchanges

<table>
<tr><th>Versions</th><th>RIBA Plan of Work (from 1964 to 1997)</th><th>RIBA Plan of Work 2007</th><th>Green Overlay to the RIBA Outline Plan of Work (2011)</th><th>BIM Overlay to the RIBA Outline Plan of Work (2012)</th><th>RIBA Plan of Work 2013</th></tr>
<tr><td>Design stages</td><td>A: Inception
B: Feasibility
C: Outline proposals
D: Scheme design
E: Detail design
F: Production info
G: Bills of Qualities
H: Tender action
J: Project planning
K: Operation on site
L: Completion
M: Feedback</td><td colspan="3">Preparation - A: Appraisal
B: Design Brief
Design - C: Concept
D: Developed Design
E: Technical Design
Pre-construction - F: Production Information
G: Tender Documentation
H: Tender Action
Construction – J: Mobilisation
K: Construction to Practical Completion
Use – L: Post Practical Completion
R and D – M: Model Maintenance and Development</td><td>0: Strategic Definition
1: Preparation and Brief
2: Concept Design
3: Developed Design
4: Technical Design
5: Construction
6: Handover and Close
7: In Use</td></tr>
<tr><td>Procurement routes</td><td colspan="4">Aligns with only one procurement route (traditional)</td><td>Offers flexibility to more routes (Customisable online version)</td></tr>
</table>

The RIBA Plan of Work 2013 (RIBA, 2013b) is accompanied by the RIBA Plan of Work Toolbox in an effort to integrate the project team (Sinclair, 2013). However, this toolkit includes no considerations for sustainability issues. For design management, a more dynamic, flexible model that also considers the different stakeholder's tasks concurrently is needed. The RIBA Plan of Work 2013 has attempted to address the fragmentation and poor coordination of design team collaboration by merely suggesting the use of the emergent technologies (e.g. BIM). However, the know-how is still missing from these processes. The implementation of a new paradigm in the design process needs to be defined, and understood, for it to become the common practice of the industry. The means and strategies, through which innovations are implemented, need to be better understood (Slaughter, 2000). However, sustainability aspects are still missing from the collaborative design process, and are been treated as an add-on. In order to achieve the target of 2020 for zero carbon buildings (European Commission, 2016), sustainability should be an integral part of design, from the very start and throughout the process. A detailed structured process for SBD can integrate sustainability considerations timely from the beginning of design (planning, briefing, and concept stages).

2.3.3.7. Efforts to integrate sustainability considerations into the design process

As discussed in the above Section, the RIBA Plan of Work 2013 mentions sustainability in a generic way, limiting considerations into a checklist, without integrating them into the design process along with the core objectives. Pelsmakers' *"Environmental Design Pocketbook"* (2011) complements the RIBA Plan of Work's checklist by clarifying the issues and suggesting appropriate strategies that should be considered at each stage by also relating them with Code for Sustainable Homes and BREEAM credits. Although the book stresses the importance of integrating the project team, it does not clarify the interdependencies of the design decisions that different stakeholders make during the design process. Sustainability considerations should be integrated in every design decision, made by each project participant, in order to be implemented holistically at the early stages of design. Cinquemani and Prior (2010) have aligned the BREEAM assessment process with the RIBA Plan of Work 2007 emphasising on the importance of good timing as crucial for SBD. Their main argument is that sustainability considerations should be embedded throughout the design process. The resulted framework includes considerations for additional specialist building design roles (e.g. ecologist). Moreover, Zerjav et al. (2013) has described an oversimplified, single dimensional, linear process for interdisciplinary collaboration.

Fazlic's (2013) *"Design strategies for environmentally sustainable residential tall buildings in the cool temperate climates of Europe and North America"* research project, has structured the sustainable design process for a very specific type of building and climate suggesting a process for the implementation of design strategies. Despite the recommendation for close collaboration of multidisciplinary design team members, she neither attempts to define their roles and responsibilities in the process nor does she define the information requirements and tasks to be undertaken. The managerial and collaborative issues of SBD are not considered in the developed process.

Shelbourn et al. (2006) have overlaid sustainability tasks to the GDPP (discussed in Section 2.3.3.4). This study has utilised the concept of approval gates, which are inherent of the GDPP. Nevertheless, sustainability considerations are presented as a separate zone that occurs in parallel to core design tasks. Moreover, Blanco (2016) has demonstrated the shortcomings of the "*checklist approach*" of sustainability guidelines by analysing SBD practices (in Melbourne, Australia), following the principles of Linkography process mapping technique (developed by Goldschmidt, 2014).

2.3.3.8. Sustainable design automation

Several researchers have attempted to automate aspects of the SBD process in order to accelerate its progress. Fargnoli et al. (2014) have presented a design management process and tool for the development of sustainable products. This process, although useful for product design, is not viable for building design where a more dynamic and flexible process is needed. Magent et al. (2010) have described a cognitive process considering the time that it takes for a designer to commit to a decision, appreciating also the iterative nature of design thinking. However, the developed model is generic with no consideration regarding the multidisciplinary nature of SBD, and the information requirements of the process.

Other attempts have focused on automating SBD aspects of the early stages; renewable energy systems (Chou and Ongkowijoyo, 2014), energy flows (Geyer, 2012), technical sub-systems (Brahme et al., 2001). These attempts have focused on a single aspect and they do not consider a holistic approach to the design of a sustainable building, and the trade-off relationships between sustainability aspects. Gerber and Lin (2014) have developed a parametric modelling tool for optimising building form within an integrated platform, considering the trade-offs of design aspects. Although useful for the novice practitioner, the suggested process becomes too restrictive, eliminating the creative freedom of the designer.

Mourshed et al. (2003) have considered SBD as a three stage process (Outline, Scheme, and Detailed Design) also including a legend for design roles for each stage. However, this framework remains generic as it neither provides details about the tasks that need to be performed, nor their relationships. Furthermore, it seems to consider only the core disciplines of design (architect, structural engineer, mechanical engineer) resulting in oversimplification of a complex process. Riley et al. (2004) have suggested *"a building design process for high performance buildings"* described in four design stages: (i) Schematic, (ii) Design Development, (iii) Construction documents, and (iv) Shop Drawing. This process also remains very simplistic considering only three functional roles: the Leader, the Consultant, and the Advisor. Al-Bizri has also examined aspects of the SBD process, identifying the requirements in a holistic manner (Clements-Croome, 2013). The process maps that have been developed for the information transfers, have utilised the Data Flow Diagram (DFD) technique (see Table 4.4). However, the developed process does not consider the extended team of experts that are essential for SBD.

2.3.4. Management of collaborative design in construction

Due to the iterative nature of design and the complexity of the outcome, especially in the case of SBD, the management of this process becomes difficult from the early stages. These are the main reasons that increase the complexity of SBD management.

Thus, researchers have highlighted the importance of architectural management (Alharbi et al., 2015) as well as information management (Hassan, 1996) for eliminating design problems. It has been argued that, design management needs a better definition (Otter and Emmitt, 2008), and this is especially critical for sustainable buildings (Rekola et al., 2012). Furthermore, it has been suggested that BIM can assist in efficient information management (Demian and Walters, 2013). Hassan (1996) has categorised design problems into the following: (i) inherent nature of design (e.g. iterative nature), (ii) technical aspects of design (e.g. lack of technical knowledge), (iii) client related (e.g. lack of appreciation of the impact of design changes), (iv) managing information (e.g. missing information), and (v) difficulties in planning design (e.g. inadequacy of planning techniques). This research focuses on addressing the information management and planning of design categories, also assisted by the current technological solutions (e.g. BIM). This sociotechnical approach to design management encompasses a holistic consideration of the parameters that influence the design process and outcome without eliminating the critical aspects that contribute to SBD. This approach aligns with the notion that collaboration at a project level is a complex mechanism of social interaction and procurement (Cicmil and Marshall, 2005).

The current business model in the construction industry remains highly fragmented, depending on paper based models of communication, causing unanticipated errors, and as a result, time delays, and additional costs (Eastman et al., 2011). Especially in the case of environmental assessment, which is usually performed too late during the design phase, resulting in inconsistencies, compromises and lost opportunities. This process involves a large amount of people and documents, which quickly become difficult to manage and coordinate (Bouchlaghem, 2012). Korkmaz et al. (2010) have examined the association between project delivery attributes and project performance outcomes, finding that *"Energy rate"* is one of the significant variables that affect the project delivery outcome. So as to improve collaborative practice productivity in the construction industry, the focus needs to be on (Doherty and Fulford, 2006): (i) strengthening of relationships to create a network of organisations that share the same values; (ii) design processes to include value engineering and lifecycle costing; (iii) creating procedures and information needs standardisation; and (iv) performing value-adding project management activities. Soetanto et al. (2015) have identified the following as the key success factors for collaborative design projects: (i) Satisfying institutional requirements and aligning with professional guidelines; (ii) Designing activities for online collaborative design; (iii) Support for collaboration; (iv) Skills for collaboration; (v) Platforms for collaboration; (vi) Skills for online collaboration; and (vii) Skills for synchronous collaboration. A holistic sociotechnical approach to BIM-enabled SBD management can address these issues.

2.3.4.1. Collaborative working dimensions

Organisational issues and people issues benefit from the use of technology for effective collaboration in construction projects (Shelbourn et al., 2007). Shelbourn et al. (2007) have defined the key areas for effective collaboration as: Business Strategy, Technology Strategy, and People Strategy. Bouchlaghem (2012) has defined effective collaboration as a function of formal and informal collaboration; the key areas of which are: business strategy, technology strategy and people strategy. The six factors that link the three key areas are: (i) vision - agreement on scope, aims and objectives; (ii) stakeholder engagement - all key participants must be consulted; (iii) trust - time and resources are the enablers; (iv) communication - a common means should be decided; (v) processes – the day to day workflows should be transparent and known to all key participants; and (vi) technologies – an agreement on technologies to be used is required to ensure collaboration.

Partnering has the potential to create the essential conditions for intergroup contact, and subsequently, impact on project performance (Anvuur and Kumaraswamy, 2007). Partnering has also been associated with trust and commitment (Katzenbach and Smith, 1993) as well as high performance and innovation (Albanese, 1994). Moreover, it has been argued that it brings advantages to quality, sustainability, human resource management, innovation, time, and cost restrictions (Egan, 1998; Eriksson, 2010).

2.3.4.2. The social aspect of designing

Valkenburg and Dorst (1998) have described the nature of team designing as an activity that relies on the team members supporting each other. Thus, defining a shared meaning of the problem, along with the alternative design solutions, from the early stages of the design process becomes critical for a successful outcome. Categorising the activity and applying appropriate design methods, presents a viable solution (Hubka and Eder, 1998; Steele, 2000).

Blessing (1994) has concluded that design is not only a complex technical process, but also a complex social process, and thus, "*a model of the design process should include the notion of teamwork".* For the interdisciplinary teamwork to be managed successfully, a flexible structure of the design process must be created and shared among the team members to assist coordination and negotiation (Peng, 1999). For that to happen effectively, the technical, social factors that influence design need to be clarified along with the way that the project team resolves conflicts (Gunther et al, 1996; cited in Steele, 2000). What drives an integrated practice to be truly a collaborative process is that it recognises the value of its team members and uses it to achieve a high performance economic value process, achieve the client's goals, and create a better-managed process for future projects (Jernigan, 2008).

Currently, the notion of prioritising the social aspects of collaboration has driven many researchers to the implementation of sociometry for construction research in order to systematically specify the relationships between actors within an organisation (Chinowsky et al., 2008; Pryke, 2012; Yang et al., 2013). Social Network Analysis (SNA) is derived from a branch of mathematics called graph theory (Prell, 2012). SNA enables of a network linking individuals, firms of other entities applications in social research (see Table 4.4). However, SNA has not yet justified its effectiveness (Ruan et al., 2013). Although SNA effectively predicts the interdependencies between project actors, it assumes that the actors are capable of performing to their best capabilities, thus it provides no quality control over the design outcome. Moreover, it lacks the stage gates of the GDCPP that are proven to improve coordinative decision-making among project participants. A socio-technical approach is considered the most appropriate in order to combine the strengths of engineering and social modelling methods to structuring the design process (Rohracher, 2001; Sackey, 2014). The structured model developed in this research, addresses the aspect of teamwork by assigning tasks to qualified team members, and then guiding their interactions within a holistic process for SBD.

2.3.4.3. Types of communication for collaboration

Laseau (2001) has considered graphic thinking as communication in three contexts: individual, team, and public. The emphasis is on better communication so that the ideas are shared. Ewenstein and Whyte (2007) have examined the effect of types and artefacts of communication for collaboration within a multidisciplinary context. It has been found that the process of representation is imbued with power. Therefore, the decision what to show, when, how, and to whom, must be managed through careful conventions (Ewenstein and Whyte, 2007). A structured process, based on the best practices, can provide assurance and improve the efficiency of communication during multidisciplinary collaboration for SBD.

Leavitt (1978) has suggested that communication in groups can vary in terms of channels available, the equality of information sharing through communication, and the degree of centralisation of the network (cited in Freeman, 1979). Emmitt and Ruikar (2013) have categorised collaborative communication as: (i) synchronous (same time) and asynchronous (different times); (ii) intrapersonal (more private) and mass communication (more public); and (iii) formal and informal channels. Bouchlaghem (2012) has categorised the possible technologies for collaboration into four categories in relation to time and place: (i) same time - same place, (ii) same place - different times, (iii) different places - same time, and (iv) different places - different times. A structured process for automated SBD workflow management can facilitate both synchronous and asynchronous communication for distributed teams' collaboration, which is the norm in construction.

The purpose of communication for collaboration is the exchange of information. Tunstall (2006) has defined three types of communication for building design: (i) talking (e.g. face to face, telephone, video conferencing), (ii) writing (e.g. emails, reports, and specifications through extranets), and (iii) images (e.g. 2D, 3D drawings, animated models, photographs). The type and accuracy of communication has significant implications on the progress of the decision-making process. A clearly defined execution planning SBD process can assist in ensuring that the right information is delivered timely.

Communication problems can be addressed by providing an audit trail where except for the explicit knowledge (who did that) also accounts for the tacit knowledge (why it was done) (Cerovsek, 2011). The capabilities of BIM are very limited concerning the *"how"*, and absent concerning the "*why*", leading to inefficiency to solve the emerging problems within the BIM environment (Dossick and Neff, 2011). To address this gap, this research project has developed a process model for SBD, which defines tasks and deliverables (explicit knowledge), as well as critical decisions points and sustainability criteria (tacit knowledge).

2.3.4.4. Information/Knowledge Management (IM/KM) and collaboration

The National Economic Development Office (NEDO) shows that more than 50% of building sites are related to poor design information (NEDO, 1987). Problems can be classified as (NEDO, 1990; cited in Hassan, 1996): (i) lack of information transfer, (ii) late information transfer, or (iii) unresolved conflict through lack of information transfer management. Manyanga (1993) has shown that the process is information driven; the decision-making process is dependent on the information that the designer has at the time the decision is made, and on whether the information package can be identified (Baldwin et al., 1998; Hassan, 1996). For SBD, it is critical for project team members to acquire BPA results before they commit to design decisions.

Knowledge Management (KM) strives to formalise the manner in which organisations exploit their knowledge by improving collaboration between groups, and capturing lessons learned, among others (Carrillo and Chinowsky, 2006). However, creating prototypes that contain only the right amount of data presents a significant challenge (Jernigan, 2008). This aspect is critical, especially between diverse experts with conflicting proposals (Plume and Mitchell, 2007). The ability to make early, informed decisions based on facts is one of the major benefits of the BIM design process, but without the notion of information sharing and access to the data, this benefit is never materialised (Jernigan, 2008). Therefore, the quality of decision-making is highly dependent on the quality of the information received as well as on the capabilities of individuals to process that information. Primarily, KM is considered a social system (Ruikar et al., 2009). Thus, agreeing on the ontological commitment for KM presents the biggest challenge for conceptual design (Wang et al., 2002). Subsequently, it has been found that large construction organisations are ahead in terms of KM due to strategic formulas and structured approaches to design implementation (Robinson et al., 2005). For this reason, this research has developed a structured approach for SBD, during concept design implementation, based on lessons learnt from the best practices. By standardising successful collaboration patterns into a holistic process, novice practitioners can perform to a level comparable to that of an expert. In addition, a standardised approach can improve coordination of remote design teams by facilitating better alignment. Other challenges for KM in construction are (Carrillo and Chinowsky, 2006): (i) limited amount of time, (ii) organisation culture, (iii) lack of standard work processes, and (iv) insufficient funding. BIM standards for collaboration are discussed in detail in Chapter 3.

2.4. Summary

The meanings of sustainable construction are diverse, depending on context and background. Some practitioners focus on the latest advances of technology, while for others sustainability is about lessons learnt from history about methods and use of materials (Wines, 2000). Others focus on topography, vegetation, solar energy or the earth itself to achieve sustainable goals. All these aspects are important for SBD, and when combined, the optimum outcome is achieved. However, for the sustainability objectives to be met, complexity of the design process is increased. Therefore, coordination among the design team about design priorities and trade-off relationships becomes a necessity. Overall, the drivers for implementing SBD have been described as the following: (i) energy consumption (Autodesk, 2005) and environmental concerns (Azhar et al., 2009), (ii) human comfort and health (Azhar et al., 2011), (iii) and financial benefits (Kats and Capital, 2003) and legislation.

Nevertheless, environmental impacts are presented as the main cause in the process for SBD (Vakili-Ardebili, 2005). Sustainable building assessment methods (rating systems) are useful to provide classification for the performance of buildings, while building assessment tools (software) can assist decision-making during the design process. A holistic process that integrates sustainability considerations comprehensively, is currently missing. For this reason, this research project aims to make sustainability targets explicit, and align them with the design teams' core tasks and responsibilities during the early stages, which are considered the most critical to achieve high environmental performance results.

Various authors have defined the high-level generic environmental design process as a three-step sequence of considerations that concern firstly the climate and context, secondly the building form and orientation, and finally, the mechanical services as supplementary solutions to the passive strategies implementation (Brown and DeKay, 2000). On the other hand, some authors have focused on the iterative nature of design, and others on its collaborative nature and management. Currently, there is no process that takes into account both dimensions and is able to facilitate the efficient implementation of collaborative SBD. Furthermore, the design synthesis and the iterative nature of design, especially at concept stage where the problem is still ill-defined, require the element of flexibility and adaptability for a more effective management of the process. For this purpose, a descriptive systematic approach to SBD process mapping is considered the most appropriate for an open system.

A paradigm shift towards integrated multidisciplinary design processes can facilitate a more sustainable building outcome. However, the RIBA Plan of Work 2013, which is currently the industry standard, fails to integrate sustainability considerations throughout the process, and the roles and responsibilities of the design team members are not defined properly. The SBD process is information driven and its management is information related; social interaction, and technological enablers and barriers, facilitate or hinder the process accordingly. The roles, responsibilities, information exchanges, methods, tools, and their interdependencies need to be made explicit in order for the design process management optimisation to happen. A CE systematic approach can be utilised to standardise repeatable processes that lead to high-value collaborative SBD. Thus, the CE process model developed in this research strives to integrate sustainability considerations throughout the design process so as to make explicit the trade-off relationships between varying areas of expertise. For this reason, the tasks, deliverables, and critical decisions points have been identified based on the workflows of the best practices for SBD. As a result of this standardised approach, better team alignment is facilitated by using the existing technological enablers so as to move from a hierarchical structure towards a centralised system architecture. The main literature findings, discussed in this Chapter, are summarised in Table 2.3.

Table 2.3 Key literature review findings of Chapter 2

SBD goals	Environmental	Use of natural resources, Pollution prevention, Environmental management
	Economic	Profit, Cost savings, Economic growth, Research and development
	Social	Standard of living, Education, Community, Equal opportunity
SBD strategies (environmental)	Passive	Massing, Daylight, Natural ventilation, Passive heating, Thermal mass, Insulation, Sound analysis
	Active	HVAC systems, Water systems, Renewable systems
	Hybrid	Midpoint solutions
SBD process (conceptual stage)	Iterative	Enabling trial and error, Eliminating rework due to lack of coordination or inaccurate information
	Collaborative	Business, Technology, and People strategies (sociotechnical approach)
	Systematic	Interdependent parts connected directly or indirectly (GST), Open versus Closed systems
	Concurrent	Multi-disciplinary, Parallel completion of tasks, Rules-based, Automation, Continuous assessment
	Standardised	Prescriptive, Descriptive, and Consensus models

Chapter 3

BIM-enabled sustainable design and delivery

3.1. Introduction

This Chapter sets the context for BIM and identifies its definitions as they exist in current publications and standards. The Chapter starts with a brief historical account of the evolution from drafting to BIM. Then, the policy, technology, and process aspects of BIM are discussed in detail. Also, the perspective of BIM as *"Building Information Management"* and the need for the development of a BIM strategy is explained. In addition, the synergies between BIM and SBD are examined along with the level of integration of sustainability aspects into BIM collaborative processes. The scope of this Chapter is to identify the areas that require improvements. To achieve that, the literature review examines the parameters (benefits, challenges, and limitations) that affect the BIM-enabled multidisciplinary collaborative SBD implementation. As a result, the Chapter reveals the gaps in the existing literature as well as the possibilities for BIM integration with sustainability information management.

3.2. Context

As discussed in Chapter 2, the role of the design manager as a separate discipline to the architect-led paradigm has emerged through the Latham (1994) and Egan (1998) reports (see Section 2.3). Furthermore, several reports have emphasised the importance of improving the quality of collaborative processes as well as the quality of the end product of building design (Kaatz et al., 2006; DTI, 2007b; National Platform for the Built Environment, 2008; Cabinet Office, 2011; HM Government, 2013). It has been argued that BIM has the potential for the implementation of quality management, leading to a more sustainable outcome (Chen and Luo, 2014).

Early CAD (Computer-Aided Drafting/Design) implementation has been mainly "*geometric centric*" (Choi et al., 1984). The focus shifted in the 1990s where the importance of integrating graphical and textual design information was acknowledged (Linderoth, 2010). Currently, building models are able to integrate a variety of engineering analysis from a wide range of construction industry professionals (Richards, 2010). So as to achieve efficient BIM implementation, the construction industry needs to rethink, and reshape, its current ways of working in order to move from fragmented processes to integrated collaborative procedures (Mao et al., 2007).

Following the recommendations by the BIM Working Group, the UK Government has mandated the use of fully collaborative 3D BIM for its projects by 2016 (BIS, 2011). The Government's Construction Strategy promotes an excellent opportunity for both the Government (and all the relevant research bodies), and the AEC/O industry to identify new forms of collaboration and working to deliver better value for money projects (Becerik-Gerber and Kensek, 2009). BIM is considered to be one way to address the deep rooted fragmentation problem in the AEC/O industry by being a computer intelligible approach to exchange building information in design between disciplines (Sacks et al., 2010).

The most effective way of achieving sustainability in a project is to consider the incorporation of environmental issues even before the design is conceptualised. Thus, it is critical to integrate sustainability into project design and assessment from an early stage, before most of the critical design decisions are made. However, sustainability assessment is usually carried out when the design of the building is almost finalised (Crawley and Aho, 1999; Soebarto and Williamson, 2001), resulting in lost opportunities. The environmental assessment methods (e.g. BREEAM) that are currently used as design guidelines for sustainability are not sufficiently ensuring that the desired objectives are going to be met (Ding, 2008).

Even though the efficient coordination of people, tools, and technology can lead to significant benefits in the quality and performance of buildings, there are many challenges to be faced. An integrated design process, interdisciplinary collaboration, complex design analysis, and careful material and system optimisation are required to solve this problem (Nofera and Korkmaz, 2010). It has been documented that despite the obvious benefits of collaborative BIM-based sustainability analysis, its use is still not widely adopted. For this reason, the readiness of construction companies to adopt new technologies is a major concern among researchers (Abuelmaatti and Ahmed, 2014; Ruikar et al., 2006; Succar and Kassem, 2015). Especially in the case of high performance buildings, the need to increase collaboration and coordination between structural, envelope, mechanical, electrical and architectural systems increases. This interaction requires attributes such as the early involvement of participants, experienced teams, levels and methods of communication and compatibility within project teams (Nofera and Korkmaz, 2010). Several authors have acknowledged the significance of managing the decision-making process when diverse experts have conflicting proposals (Plume and Mitchell, 2007). These communication problems can be addressed by providing an audit trail (how it is done) where except for the explicit knowledge (who did what when) also accounts for the tacit knowledge (why was it done) (Cerovsek, 2011). Recent research has revealed that the current capabilities of BIM are very limited concerning the *"how",* and absent concerning the *"why",* leading to inefficiency to solve the emerging problems that occurred during the design process (Dossick and Neff, 2011). Nevertheless, the amount of information generated, significantly increases the complexity of the process. As a result, the coordination of design components becomes even more challenging. This study has developed a systematic process for BIM-enabled SBD, which can be used as a guideline for design implementation, while also combining expert knowledge for decision-making against defined criteria.

3.3. Towards a definition of BIM

This Section starts with a brief historical account of evolution from drafting to BIM. Then, the definitions of BIM and the various standards that have been developed for this purpose are presented. The concept of *"BIM maturity"* is explained and its effect on project delivery methods is examined.

3.3.1. From drafting to BIM

Traditionally, building design illustrations have been hand-drawn on paper using instruments such as pen, T-square, drawing board, paper, and irregular curves (Henderson, 1994). To this date, hand drawings are still being generated, by the architects, as means of communication with the rest of the design team, during the early stages of the design synthesis. Hand drawing has firm supporters, who stress the importance of maintaining it as part of the curricula in design education, as well as in professional practice, while integrating it with the digital technologies (Have and Van den Toorn, 2012; Lyn and Dulaney Jr, 2009).

The invention of CAD has addressed shortcomings of paper-based design such as time consumption, and limitation in alterations to the original drawing. The adoption of 2D CAD became widespread in the 1990s and within a decade it was developed to 3D CAD (Sackey, 2014). Later on, the term *"Building Information Model"* has been first published by van Nederveen and Tolman (1992). Varying terminology has been utilised by different software companies (Graphisoft, *"Virtual Building"*; Bentley Systems, *"Integrated Project Models"*; Autodesk and Vectorworks, "*Building Information Modeling*"). Design implementation has been benefiting from the above technological advancements that facilitate the efficient communication of the designers' intent.

It has been noted that BIM has been the most significant step change in the construction industry since the emergence of 2D CAD. For this reason, the processes for its implementation remain to be understood. This paradigm shift towards parametric modelling is fundamentally different from the traditional drawings. The new paradigm suggests that the design product can be represented by a database of information and relationships, rather than a set of abstract representations that are subject to interpretation (Denzer and Hedges, 2008). Furthermore, the increasing amount of information, related to decision-making during contemporary building design, increases the complexity of the management process (Krygiel and Nies, 2008). Thus, in order to address this step change effectively, the new methods and processes need to be defined and formalised.

3.3.2. Defining BIM

The NBIMS (2007) document has defined BIM as:

> *"A digital representation of physical and functional characteristics of a facility. As such it serves as a shared knowledge resource for information about a facility forming a reliable basis for decisions during its lifecycle from inception onward."*

Furthermore, RIBA Enterprises Ltd and NBS (2017) state that:

> *"BIM describes the means by which everyone can understand a building through the use of a digital model which draws on a range of data assembled collaboratively, before during and after construction. Creating a digital Building Information Model enables those who interact with the building to optimize their actions, resulting in a greater whole life value for the asset."*

The above definitions suggest that every piece of information should be connected somehow to the BIM model electronically so that it can be retrieved when needed. Thus, BIM software can be utilised to plan, design, construct, operate, and maintain buildings collaboratively utilising standardised approaches. It is argued that BIM can create value by combining the efforts of people, process, and technology (RIBA Enterprises Ltd and NBS, 2017). Several authors have developed BIM definitions, which consider the following aspects: (i) people, tools, and processes (DTI, 2007b); (ii) process, technology, and competence (Rekola et al, 2010); (iii) technology, process, and people (Chen, 2014); and (iv) policy, technology, and process (Succar, 2009; Succar et al., 2012; Succar and Kassem, 2015). However, there is still limited understanding of the ways that sustainability information can be integrated within BIM.

3.3.3. BIM maturity

Although the definitions of BIM maturity continue to be evolving (Kassem et al., 2015; Succar et al., 2012), the delivery of co-ordinated graphical and non-graphical project information is the main subject. Several attempts have been made to benchmark the maturity of BIM implementation (NBIMS, 2007; Succar et al., 2012; Succar, 2009). In the UK, the BIM Maturity Diagram (shown in Figure 3.1) is the most commonly used definition (Richards, 2010). The diagram defines the four levels of BIM collaborative process management into (0 to 3): Level 0 represents an unstructured process of exchanging CAD files and paper based documents; Level 1 process is defined as file-based collaboration following specified information management standard guides; Level 2 aligns with the same standard guides but also suggests that the software models of various stakeholders are coordinated and that there is a common library management, or else a Common Data Environment (CDE), for sharing and downloading files for collaboration; Level 3 is envisioned as fully integrated and interoperable data, which follow common interoperability standards. This research aims to understand the current practices for implementing BIM-enabled sustainable design, and assist towards increasing its maturity from "*ad hoc*" to "*defined*", and then, to "*managed*", as described by Succar et al. (2012).

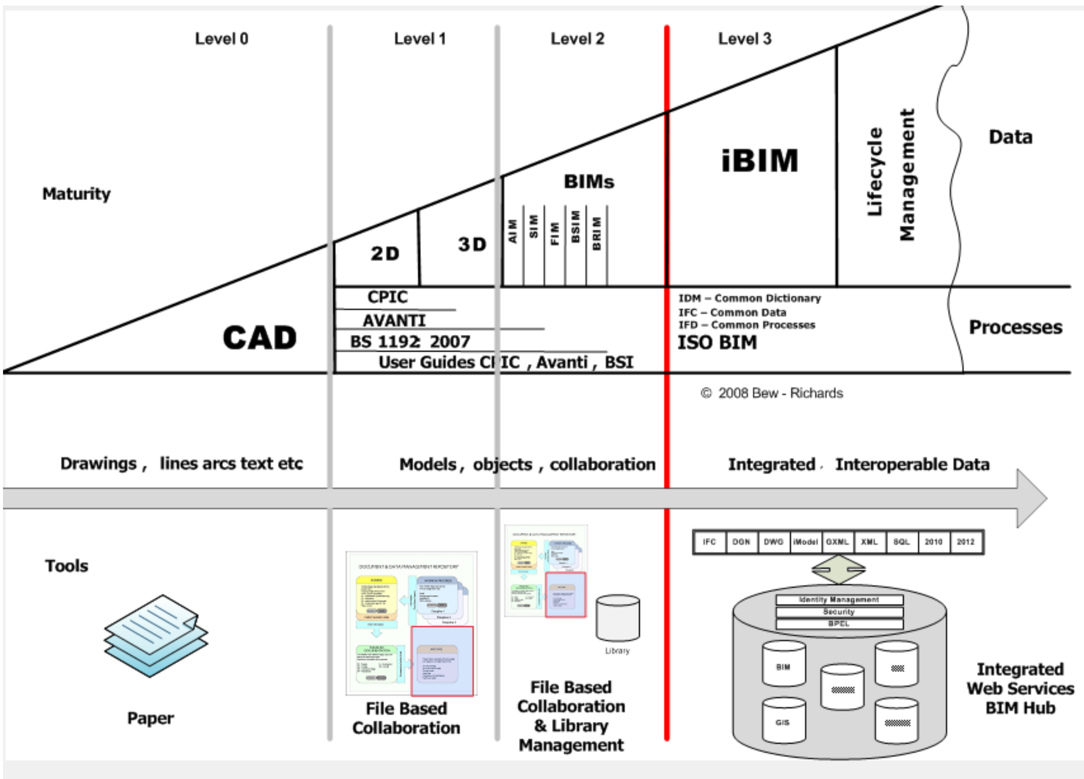


Figure 3.1 BIM Maturity Diagram (Richards, 2010)

Level 2 BIM Maturity (Richards, 2010) requires the exchange of information within a CDE following BS1192:2007 for the delivery of information (BSI, 2007). The CDE acts as a central repository for the model, where the local copies are synchronised (see Figure 3.2). These files are named as Work In Progress (WIP), Shared, or Archived, following a specified exchange protocol. This way, the files are accessible by project participants through controlled access. Before sharing, the model needs to be checked, approved, and validated (as defined in the BIM Project Strategy document) (Richards, 2010) so as to be ready for coordination. All external information should be included in the CDE as well. In the UK, a number of BSI standards have been developed in order to define Level 2 BIM maturity and create a common language for BIM-enabled collaborative design (see Section 3.5.1) (Building Research Establishment Ltd., 2016). However, their uptake remains low (Cousins and Knutt, 2016). This research draws upon the existing BIM implementation standards, striving to incorporate sustainability considerations throughout the design process, for the early stages.

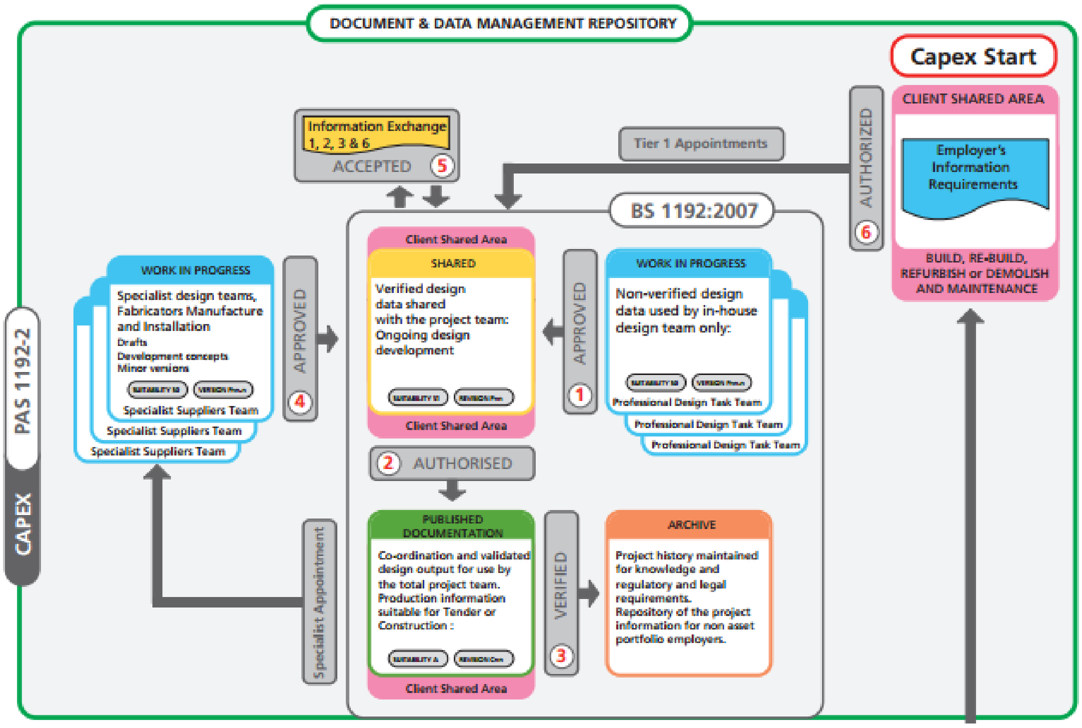


Figure 3.2 Information management within a CDE (BSI, 2013b)

It needs to be clarified though that Level 2 BIM maturity is not a single building model or a single database; it is more a series of interconnected models and databases. These models can take many forms while maintaining relationships and allowing information to be extracted and shared. The single model or single database description is one of the major confusions about BIM, among the following (Jernigan, 2008): (i) BIM is not a replacement of people, it is still a lot of work, but it lets people work smarter; (ii) BIM will not automate every process, it is still required to use individual problem-solving skills with less effort; (iii) BIM can assist in capturing knowledge, reduce repetitive inputs, and errors are easier to find.

3.4. Building Information Management

"Building Information Modelling" can be rephrased as *"Building Information Management"* or *"Better Information Management";* whichever the definition, the *"heart"* of BIM is information. Crotty (2012) points out that the impact of poor information on the design process leads to significant problems. In fact, the most prominent reason for failures has been missing, or inadequate, project information (NEDO, 1987). Poor communication among the design team is also a common deficiency (Crotty, 2012). Collaborative information management is considered one of the critical issues in construction management (Demian and Walters, 2013; Erdogan et al., 2008; Finch et al., 2007; Motawa and Carter, 2013). Attia et al. (2013) have reported that there have been very few studies that attempt to model the design process of high performance buildings with an integrated team. However, their suggested solution is a sequential process. For concept design, a more detailed definition is essential since its complexity increases significantly.

3.4.1. Computer Supported Collaborative Design (CSCD)

The traditional point-to-point model has proven to be complex and inefficient, and a data-centric model has been suggested instead as optimal (Yu, 2014). Technology is considered the tool that can support process improvements and assist the role of the project manager (Cooper, 2005). Thus, CSCD has seen a quick advancement due to the Internet and Web-based technologies. It is considered as the way to address the requirements resulting from increasingly complex product development (Shen et al., 2008). For the communication of information among project team members, the use of Online Collaboration Platforms (OCPs) is essential from the early stages of the design process (Anumba et al., 2002). It has been suggested that all communication and collaboration should take place through BIM (Jernigan, 2008). Thus, the use of OCPs is important, as they enable both the synchronous and asynchronous collaboration that is needed in BIM collaborative processes (Anumba et al., 2002).

The existing technological maturity (e.g. processing power of computers, server capacity, internet connection, BIM) creates the need to redesign the existing collaborative design processes so as to enhance the centrality of information and exploit the benefits of cloud computing (Ruikar et al., 2003). This approach has also been referred to as Integrated Project Delivery (IPD) (Autodesk, 2008; Glick and Guggemos, 2009; Rekola et al., 2010) (see Section 3.4.3). In the case of complex high performance building design, the efficient integration of information becomes more crucial than ever.

As BIM models quickly become large and complex, data coordination and task management becomes a major concern (Eastman et al., 2011). Eastman et al. (2011) discuss the issues that any planner for 4D modelling should consider: (i) model scope, (ii) Level of Detail, (iii) re-organisation of the model, (iv) temporary components, (v) decomposition and aggregation, and (vi) schedule properties. The NBS BIM Toolkit Level 2 BIM package of standards, helps employers specify the information requirements (Employers Information Requirements, EIR) and also validate if those have been provided to them. Nevertheless, several additions are needed in order to accommodate truly collaborative SBD. The reason behind this gap is the lack of a proper definition of the SBD process. Robinson et al. (2005) have suggested that, for sustainability, knowledge management should: (i) be linked to all business objectives; (ii) be practiced diffused in the entire organisation; (iii) be embedded in the culture, employers behaviour, business processes, and product development; and (iv) be reported for its performance.

A systematic approach to information management would secure that project participants acquire the right information at the right time. To achieve that level of coordination, ad hoc processes that lead to a spider web communication diagram should be kept to a minimum, while enabling centralisation of information in a CDE. Thompson et al. (2009) have stressed the importance of managing knowledge of urban sustainability assessment, and has developed a methodology for the system. Furthermore, Verheij and Augenbroe (2006) have emphasised the need for better project planning, which is Web-based, and driven by a series of detailed workflows.

3.4.2. Project delivery for sustainable buildings

Project delivery processes include programming, procurement, design, construction, and turnover (Lapinski et al., 2006). Ghassemi and Becerik-Gerber (2011) have identified the following aspects, which differentiate collaborative project delivery to traditional one: (i) early and continuous involvement of key stakeholders; (ii) clear roles and responsibilities, and clear communication lines; (iii) integrated project team consisting of client, designers, constructors and specialist suppliers, facilities managers; (iv) common goals and collaborative decision-making; and (v) an integrated design process where design, construction, and operation are considered as a whole. Smith (2003) has suggested that misunderstanding a project's characteristics is likely to lead to defective delivery processes and higher costs (cited in Nofera and Korkmaz, 2010). For that reason, the planning of design implementation becomes even more critical as the complexity of design increases.

Unlike traditional buildings, sustainable ones have more delivery constraints (Horman et al., 2006; Kibert, 2007; Riley et al., 2004). Characterised by technical systems with high levels of interdependency and interaction, these buildings demand increased levels of design collaboration and coordination between structural, envelope, mechanical, electrical, and architectural systems during SBD (Magent et al., 2010). This interdisciplinary interaction suggests that attributes such as early involvement of participants (Riley et al., 2004), team experience (Winter, 2014), levels and methods of communication, and compatibility within project teams, result in better outcomes (Horman et al., 2006; Lapinski et al., 2006). Research has shown that early introduction of sustainability, and owners' commitment to sustainability, enables the achievement of SBD goals at lower costs (Horman et al., 2006; Nofera and Korkmaz, 2010).

3.4.3. Integrated Project Delivery (IPD)

The American Institute of Architects (AIA) has defined IPD as (AIA, 2007):

> *"A collaborative alliance of people, systems, business structures and practices into a process that harnesses the talents and insights of all participants to optimise project results, increase value to the owner, reduce waste, and maximise efficiency through all phases of design, fabrication, and construction"*

The focus of an IPD process is the management of information, which is used throughout the process, so as to allow stakeholders to make informed decisions (Hardin, 2009). The benefits of IPD have been discussed extensively in the literature (Becerik-Gerber and Kensek, 2009; Dave et al., 2013; Ghassemi and Becerik-Gerber, 2011; Glick and Guggemos, 2009; Holland et al., 2010; Jernigan, 2008; Solnosky et al., 2013). The current shift towards IPD requires a significant change in the design firms' quality and nature of services (Eastman et al., 2011). Arguably, a successful sustainability outcome is considered a measure of design quality. Increasing complexity in the building process requires an extensive array of design and construction specialists from diverse disciplines and multiple firms to work together in temporary teams (Dossick and Neff, 2011). It has been proven that specialist knowledge from a range of experts is essential for high performance intelligent buildings (Clements-Croome, 2013). This is crucial especially in larger and more complex building schemes that have high environmental ambitions (Pelsmakers, 2011). The deficiencies of the design process occur due to inefficient coordination and communication between stakeholders that leads to inappropriate timing to make critical decisions (Magent et al., 2009). Therefore, acknowledging the roles of specialty contractors in SBD, and their potential added-value, is critical in order to upstream decisions and processes. The early entry of stakeholders and their functionaries, with an emphasis on the design and planning, can minimize error and reviewing during the construction phase (Cooper et al., 2008).

This research argues that IPD is the way to achieve the client's sustainability goals efficiently. For that to happen, the roles, responsibilities, and implementation of SBD need to be defined and made explicit. Coordination between a wide range of professionals becomes complex and difficult to manage without the proper processes in place. A commonly agreed process can improve communication and coordination of the design participants, who are essential for sustainability. To achieve that, the input of all parties, including specialist subcontractors and consultants, is needed (Hardin, 2009).

The MacLeamy curve (CURT, 2004) supports the notion that the traditional schedules and processes need to be re-designed for the implementation of IPD (Weisheng Lu et al., 2014). To date, RIBA has not updated their recommendations regarding the "*project programme*" (see Sinclair, 2013). The recommended programmes do not align with the BIM schedules, where the design is front-loaded, and as a consequence, requires more time upfront in comparison with the traditional project programmes. The RIBA Plan of Work's 2013 programming aligns with the traditional schedules of the Boehm's curve (1976) and not the IPD ones (cited in Davis, 2016).

The defining characteristics of IPD include (AIA, 2007): (i) highly collaborative processes that span building design, construction, and project handover; (ii) leveraging the early contributions of individual expertise; (iii) open information sharing amongst project stakeholders; (iv) team success tied to project success, with shared risk and reward; (v) value-based decision making; (vi) and full utilization of enabling technological capabilities and support. Owen et al. (2010) have identified that the challenges for integrated design and delivery lay within four categories: (i) collaborative processes, (ii) enhanced skills, (iii) integrated information and automation systems, and (iv) knowledge management. This research aims to facilitate IPD for SBD by identifying the level of expertise of participants, and defining their contribution during the early stages of design into a coordinated process, which is assessed towards specified sustainability criteria.

3.4.4. BIM-enabled sustainability strategy

Defined strategies enable the organisation to adapt to the changes of the external world. Therefore, it is essential that a strategy is viable, taking into account the organisation's abilities as well as the opportunities presented by the environment (Jennings and Wattam, 1998). Benchmarking BIM performance can raise awareness and help the design team to establish a common strategy for BIM implementation (Sebastian and van Berlo, 2010). Various authors have recognised the need for a clear path for BIM (Jernigan, 2008). Nonetheless, the fragmented nature of the building industry, where each design specialist has their own view and set of objectives, does not facilitate integration. Design collaboration works best when these specialists adopt a *''super-paradigm''*, agreeing to a course of action to achieve a common goal for the whole project, rather than narrowly considering their own objectives in isolation (Mignone et al., 2016; Plume and Mitchell, 2007). The need for complementary socio-technical methodologies for BIM implementation strategies has been emphasised by various authors as well (Arayici et al., 2011; Khosrowshahi and Arayici, 2012; Sackey, 2014). For that to happen, the AEC/O organisations need to rethink their working processes (Eastman et al., 2011).

Mulvihill and Jacobs (1998) have discussed about the scoping stage in building assessment consisting of: (i) establishing and refining the project vision and objectives based on sustainable development's principles and stakeholders' needs; (ii) establishing common values; (iii) identification of contextual issues that influence the problem definition; (iv) identification of significant assessment issues based on social values and professional judgment; (v) development of terms of reference for the stages of the assessment process; and (vi) scheduling all critical decision-points in the project's life cycle along with the identification of the information needed. Furthermore, Hardin (2009) has argued the importance of a plan for sustainability, as part of the scoping stage, one that identifies the sustainability goals for a project. The sustainability plan should consist of: (i) project summary, (ii) accreditation goal summary, (iii) local recycling resources, (iv) local municipal sustainability initiatives, (v) project limits (e.g. VOCs, construction waste), (vi) project initiatives (e.g. green energy credits, on-site energy demand), and (vi) evaluation. This fact means that sustainability considerations, and assessment, should occur during strategic planning and briefing (i.e. RIBA stages 0 and 1). To date, there is no standardised method to assist practitioners plan the implementation of sustainability goals. Information sharing, and thus, the success of the sustainability outcome, relies on individual ad hoc practices (Cheng and Das, 2014). Commitments should be made from the inception of the project, and they should be as specific as possible, before being communicated among the design team. For that to happen, the goals, roles and responsibilities have to be formalised from the beginning (Krygiel and Nies, 2008). However, nothing of such exists for SBD so as to control its successful outcome.

It is apparent that strategic project management for SBD is needed. The definition of roles and rules that govern the SBD process, as well as guidelines for collaboration workflows need to be better defined. In addition, the delivery of sustainability information, and its integration with BIM, is not clear in the literature. Providing such definitions can facilitate the use of technological solutions, but comprehensive planning of the organisational structures is needed first, before they can be realised. It is argued that a big gap exists in the RIBA Plan of Work 2013, which is the commonly used standard in the UK, and the same stands for the CDE structured approaches and standards. A more comprehensive approach to strategic project management of SBD is necessary, one that bridges the gap between the two. The NBS Toolkit is a significant contribution towards this direction but sustainability has not been considered sufficiently.

3.4.5. BIM Execution Planning (BEP) for sustainable design

Despite the various standards and protocols that have been released to define BIM, the practical experience for its implementation is still lacking (Hooper and Ekholm, 2012). Thus, the need for the development of a *"BIM Execution Plan"* (BEP), before the actual design starts, has been established (Race, 2012; RIBA, 2012; Sinclair, 2013). The plan's intention is to define the roles, responsibilities, and duties of the different stakeholders according to the BIM deliverables for each design stage. The "*BIM Project Execution Planning Guide*" (CIC, 2011) has been developed to assist organisations maximise BIM implementation focusing on the activities, messages, and events that are executed to achieve a common goal (Kreider and Messner, 2013).

The six elements that should be considered when developing an action plan for BIM implementation are (CIC, 2011): (i) the strategy – includes the goals and objectives, as well as the management support; (ii) the uses – describe the specific method of implementing BIM including creation, processing, communication, and integration of information; (iii) the process – focuses on the existing workflows and adapts those to BIM; (iv) the information – defines the information requirements (e.g. model element breakdown, level of development, and data); (v) the infrastructure – includes the software, hardware, and workspaces needed; and (vi) the personnel – examines the roles and responsibilities, education and training. Wu and Issa (2014) have developed a guide to assist towards BIM and IPD implementation for SBD. However, the guide is limited to the traditional disciplines of design, and sustainability execution planning refers only to the LEED rating system. The roles, responsibilities, and deliverables should be defined first, before attempting the re-engineering of the process.

Others have suggested that a BEP should address as a minimum the following (Jernigan, 2008): (i) goals and uses – define the project's BIM goals, uses, and aspirations along with workflows required to deliver them; (ii) standards – BIM standards used for the project, and any deviations from the standards; (iii) software platform – define the BIM software to be utilised and how interoperability issues are addressed; (iv) stakeholders – identify the project leadership and additional stakeholders, as well as their roles and responsibilities; (v) meetings – define meeting frequency and attendees; (vi) project deliverables – define the deliverables and the format in which they are delivered; (vii) project characteristics – number of buildings, location etc., and division of work and schedule; (viii) shared coordinates – define the common coordinate system for all BIM data (e.g. detailed modifications, imported DWG/DGN coordinates); (ix) data segregation - address model organisational structures to enable multi-discipline, multi-user access and project phasing as well as ownership of the data; (x) checking/validation – define checking and validation process of drawings and BIM data; (xi) data exchange – define the communication protocols along with the frequency and form of data exchange; and (xii) project review dates – set out the key dates for reviews of the BIM, which both internal and external design teams participate.

It is suggested that developing a BEP can be challenging, as very often, there is conflict between design objectives. For this reason, the need for a holistic point of view from the early stages of design, is necessary. BIM combined with a range of BPA software, that support interoperability standards, can facilitate the management of sustainability information through a building's life cycle. A dynamic process is necessary in order to assess, and re-assess, those aspects iteratively during the design development. Thus, the roles of the sustainability specialists, as well as the sustainability considerations of the key design players, need to become understood, and integrated, within the core activities of design. This research supports the notion that BIM implementation strategies should be made explicit, for SBD, and the interdependencies of components should be communicated, and agreed, amongst the design team before design starts.

3.5. Fields of BIM implementation

The AEC/O sector has been criticised concerning its slow adoption of innovative technologies (Nicolini, 2002). The reasons that have been identified are the heterogeneous and bespoke nature of its services (Sackey, 2014), along with the complexity of project delivery (Anumba, 2000; Dainty, 2008). In order to reap the benefits of BIM, in the construction industry, the traditional project delivery methods need to be challenged from planning, to design, and throughout the lifecycle of the building from inception to completion, and demolition. It has been proven though that BIM implementation is as much about people and processes, as it is about technology (Arayici et al., 2011; Ahmed et al., 2016). Therefore, the bottom-up perspective should inform the top-down; which means that tasks undertaken during design implementation should inform the organisational perspective of the SBD process.

Successful implementation of collaboration systems depends 80% on tackling people and process issues, and 20% on resolving technology issues (Wilkinson, 2005). The resistance to technology has two broad areas (ibid.): principle of collaborative working, and the adoption of the technology itself. For successful collaboration to be achieved, a combination of people, processes, and technologies is required. However, the people aspects present the biggest challenge (Soetanto et al., 2003). In the absence of well-defined strategies that take into account organisational, project, and user requirements, the implementation of a collaborative system is happening in an ad hoc manner (Bouchlaghem, 2012; Pala and Bouchlaghem, 2012).

So as to achieve the successful implementation of BIM, for SBD, a paradigm shift is required. The standardisation of repeatable processes could facilitate their automation and therefore, streamline the collaborative design process. For this purpose, more sophisticated contractual terms and guidelines, demand for people with new skills, new management roles, green building design, interaction information workspaces, automated verification tools, construction management functions integrated in BIM, and peripheral hardware are needed (Eastman et al., 2011). Moreover, a plan for the implementation of BIM is imperative before the conversion begins (ibid.). However, currently there is no method for the planning and delivery of sustainability information. This research aims to address this gap by defining the early stages of SBD, namely, the RIBA Plan of Work's (2013) stage 0 "*strategic definition*", stage 1 "*preparation and brief*", and stage 2 "*concept design*".

Several publications have developed BIM frameworks, which include the following categories: (i) people, tools, and processes (DTI, 2007b); (ii) process, technology, and competence (Rekola et al, 2010); (iii) technology, process, and people (Chen, 2014); (iv) business, technology, and people (Shelbourn et al., 2007); and (v) policy, technology, and process (Succar, 2009; Succar et al., 2012; Succar and Kassem, 2015). Nevertheless, the framework developed by Succar (2009) has been found to be the most comprehensive. It consists of three BIM fields: (i) the policy field, (ii) the technology field, and (iii) the process field (see Figure 3.3). The players of the policy field are research centres and regulatory bodies, among others. The second BIM field is the technology field; the identified players are the software developers that provide the required technology to both aforementioned bodies. Finally, the players of the process field are the AEC/O stakeholders, which are responsible from the pre-design to operation phase of a project. The project deliverables occur from the push-pull interaction of knowledge between two of the above players. Furthermore, Rekola et al. (2010) have highlighted the importance of process mapping for business organisational change, but sustainability considerations have not been included in their model. This research project's scope is to define the process of conducting SBD, and assessment, at the early stages. Nevertheless, the policy and technology fields are constraints that affect the SBD process, and need to be examined in detail.

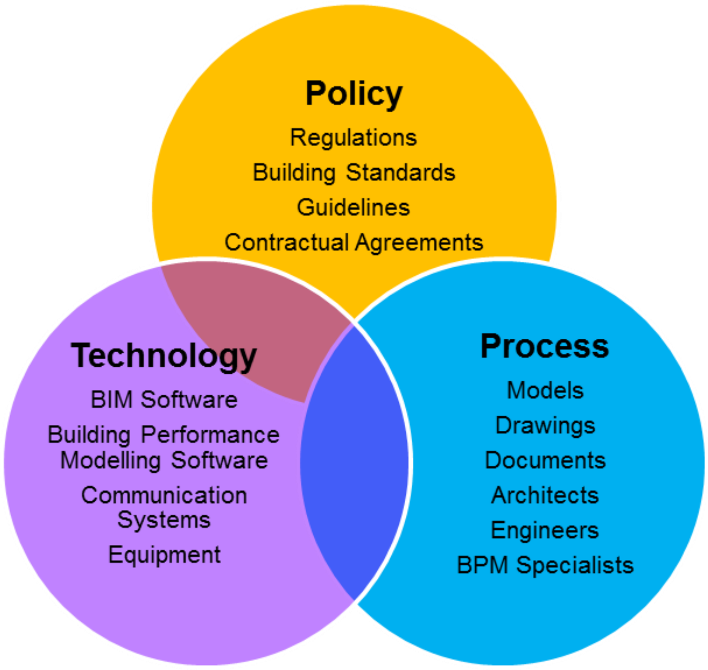


Figure 3.3 Interlocking fields of BIM activity (adapted from Succar, 2009)

3.5.1. Policy field

This Section examines the policies that relate to BIM and SBD. Kasim (2015) has examined the prospect of enabling the automatic checking of a BIM model against a set of regulations. In this research study, the UK policies and regulations are considered as both enablers and drivers, but also, as constraints of the design process. The following sub-Sections present the main policy makers and regulations, which guide the SBD by setting the sustainability performance criteria and benchmarks that need to be realised for compliance.

3.5.1.1. Policy makers and regulations

As discussed in Chapter 2 (Section 2.3), a number of reports have addressed the chronic AEC/O industry traits in an effort to improve efficiency and effectiveness in construction processes, which would ultimately lead to greater value for the client (Murray and Langford, 2003). The UK Construction Strategy (Cabinet Office, 2011) has demanded collaborative Level 2 BIM maturity by 2016, and this fact has led to the formation of groups and organisations to respond to this need (e.g. BIM Task Group, BIM2050 Group, buildingSMART, Avanti), while existing organisations have shifted their focus accordingly (RIBA, 2012a; RIBA, 2013b; Building Research Establishment Ltd, 2016). As an example, the BRE (Building Research Establishment) has developed schemes for proving BIM compliance certification. Additionally, National Building Specification (NBS), owned by RIBA, has published research for BIM adoption in the UK.

The UK Government has defined Level 2 BIM maturity with the following standards (NBS, 2015b; NBS, 2016):

1. PAS 11922: 2013 - Specification for information management for the capital/delivery phase of construction projects using building information modelling (BSI, 2013b).
2. PAS 11923:2014 - Specification for information management for the operational phase of assets using building information modelling (BSI, 2014b).
3. BS 11924-4:2014 - Collaborative production of information. Part 4: Fulfilling employer's information exchange requirements using COBie (Construction Operations Building Information Exchange) – Code of practice (BSI, 2014c).
4. Construction Industry Council (CIC) Building Information Model (BIM) Protocol - This establishes specific obligations, liabilities and limitations on the use of building information models and can be adopted by clients to mandate particular working practices. It can be incorporated into appointments or contracts by a model enabling amendment (CIC, 2013).
5. GSL (Government Soft Landings) – Developed to champion better outcomes for the UK's built assets during the design and construction stages, powered by BIM, so as to ensure that value is achieved in the operational lifecycle of an asset (BIM Task Group, 2013).
6. Digital Plan of Work (DPoW) - BIM Toolkit. Developed by NBS to help define roles and responsibilities for preparing information, along with a verification

tool to identify correctly classified objects and confirm that required data is present in the model (RIBA, 2013a; RIBA, 2013b; NBS, 2015a).

7. Classification - Uniclass2015. A classification system that can be used to organise information throughout all aspects of the design and construction process (RIBA Enterprises and NBS, 2016).
8. PAS 1192-5:2015; Specification for security-minded building information management, digital built environments and smart asset management. Provides guidance on how to secure the intellectual property, the physical asset, the processes, the technology, the people, and the information associated with the asset (BSI, 2015b).
9. BS 8536:2015; Facilities Management (FM) briefing for design and construction. For building’s infrastructure, guidance upon the definition of required social, environmental, and economic outcomes as well as the process of achieving those required outcomes (BSI, 2015a).
10. BS 8541; Range of standards for library objects (architectural, engineering, and construction) (BSI, 2014d).

The Construction Project Information Committee (CPIC) is responsible for providing best practice guidance on construction production information. It has been formed by representatives of major UK industry institutions. This has happened in order to ensure an agreed starting point, as different interpretations of the term have been hampering adoption. Still, the UK AEC/O industry adopts a fairly simple generic scheme which is outlined by the RIBA Plan of Work 2013. Therefore the suggested process remains ill-defined, treating sustainability considerations as an add-on, and not as part of the core design process, and main tasks. Evidently, the NBS National BIM reports (NBS, 2015b; NBS, 2016) confirm the adoption of the RIBA Plan of Work as the predominant standard for the management of the design process (71% and 40% respectively).

The DPoW originated as an idea from the BIM Task Group, a group supported by the Department for Business Innovation and Skills (BIS) and the CIC to bring together expertise from industry, Government, institutes, and academia to strengthen the public sector's capability at BIM. A DPoW enables an employer to outline the information requirements and define the deliverables required at each stage of a construction project from developing the strategy through to managing the asset. The NBS proposal, called the "*BIM toolkit*", intends to provide step-by-step support to define, manage, and validate responsibility for information development and delivery at each stage of the asset lifecycle, in accordance with the Government-mandated use of Level 2 BIM on all public sector projects by 2016. The BIM toolkit aligns with the RIBA Plan of Work 2013 by adopting the same design stages (0 to 7), along with definitions of roles, tasks, and information needs. The DPoW may also be exported to Microsoft Excel format for inclusion within the EIR document. The Uniclass2015 classification is employed during information delivery to organise library definitions of over 5,700 items across all construction disciplines. The beta version, released in April 2015, uses the xBIM toolkit to import and export the DPoW in either IFC (Industry Foundation Classes) or COBie format (discussed in Section 3.5.2.2 in detail), as well as to verify and validate that the information that is required has been provided by those allocated responsibility for it. Nevertheless, there is still no BIM toolkit that integrates sustainability considerations (roles, responsibilities, tasks, and deliverables) within a DPoW.

Apart from the rating systems and Part L of the Building Regulations, there are a number of policies that relate to aspects of sustainability. The National Planning Policy Framework (published in March 2012) provides guidance to local councils in drawing up local plans and on making decisions on planning applications. Based on this guidance, it is required that each local planning authority is to prepare a Local Development Framework (LDF) which outlines how planning will be managed for that area. Furthermore, a number of standards refer to carbon foot-printing (or else embodied carbon): (i) BSI - PAS 2050:2011 Specification for the assessment of the life cycle greenhouse gas emissions of goods and services; (ii) BS EN ISO 14064:2012 Greenhouse gases. Specification with guidance at the organization level for quantification and reporting of greenhouse gas emissions and removals (in three parts); (iii) GHG (Green House Gas) Protocol Standards; greenhouse gas accounting standards. Another policy is the Waste Framework Directive (2008/98/EC); article 40 has required EU member states to bring into force the laws, regulations and administrative provisions necessary to comply with this Directive by 2010. Moreover, the European Standards Technical Committee CEN/TC350 has developed a number of standards for the environmental performance of buildings (such as BS EN 15643-1, BS EN 15643-2, BS EN 15804, BS EN 15978, and BS EN 16309). Also, BS EN 15804 provides core Product Category Rules (PCR) for Type III Environmental Product Declarations (EPD) for any construction product and construction service.

The above mentioned standards, are currently used as benchmarks for sustainability objectives such as energy performance, and carbon footprint of materials. Designers assess the evolving design towards the criteria, metrics, and benchmarks provided by these standards in order to make critical decisions. Therefore, the success and failure of the sustainability outcome is judged based on whether compliance is achieved. For this reason, assessment towards performance criteria needs to be considered timely during design development so as not to miss opportunities. Zapata-Poveda and Tweed (2014) have examined the policies that are followed in the design of low carbon buildings in England and Wales. Compliance for BREEAM, and Part L of the building regulations have been found to be the most commonly used policies at the Building Control and Planning Application gateways of the building process. It should also be noted that current environmental assessment methods are designed to evaluate building projects at the later design stage so as to provide an indication of the environmental performance of buildings. However, by this stage it is too late to consider environmental issues for the first instance during SBD development (Ding, 2008).

The GSL framework has been developed by the Building Services Research and Information Association (BSRIA) in order to close the loop between design, construction, and feedback into design (BIM Task Group, 2013). The BSRIA BG4/2009 framework aligns with the RIBA Plan of Work by adding five parallel stages to the RIBA ones: stage 1 – inception and briefing; stage 2 – design development and review; stage 3 – pre-handover; stage 4 – initial aftercare; stage 5 – years 1-3 extended aftercare and Post Occupancy Evaluation (POE). Each stage consists of a checklist that describes the supporting activities that should take place. GSL stage 1 aligns with the

RIBA stage 1 "*Preparation and brief*"; the suggested activities are the following: (i) define roles and responsibilities, (ii) review past experience, (iii) plan for intermediate evaluations and reality checks, (iv) set environmental and other performance targets, (v) sign-off gateways, and (vi) incentives related to performance outcomes. GSL stage 2 starts at "*Concept design*" (RIBA stage 2) and is ongoing until "*Construction*" (RIBA stage 5). The supporting activities for stage 2 are: (i) review past experience, (ii) design reviews, and (iii) tender documentation evaluation. The framework has been developed further (April 2013) in order to adapt to the BIM Government requirements. However, the guidance for the implementation of the supporting activities remains too open and generic, and no specific recommendations are provided. Thus, it is argued that there is a need for a more detailed process, which is governed by specific rules, to assist practitioners with the execution planning of the SBD process.

Evidently, the need for greater clarity and flexibility remains (Meacham et al., 2005). Regulatory effectives of performance based design relies upon the following issues (Meacham et al., 2005): (i) better linkages and interrelationship between goals, objectives, criteria, test methods, and design tools and methods; (ii) understanding local and regional climate change and the resulting environmental effects; (iii) identifying the relationship between performance regulation and the life cycle of a building; (iv) understanding reliability and accountability of all the actors; (v) relationship between political or economic changes in a regulated area; (vi) market-driven instruments' context; (vii) methods to help identify emerging hazards and threats; (viii) identification of societal expectations and development of performance goals or objectives, which lead to development of tools, mechanisms and criteria to define, measure, calculate, estimate, and predict the desired performance.

Therefore, the overall scope of this research is to develop a BIM-enabled process for SBD in order to move from ad hoc collaboration workflows to defined ones, which address clear sustainability goals and objectives, utilising proven tools and methods. The model developed, in this research, complements the RIBA Plan of Work 2013 with evidence from existing practice, and contributes to its ongoing evolution. This research attempts to bridge the gap between common practice (RIBA Plan of Work) and the mandated fully collaborative Level 2 BIM maturity, with experience gained from early adopters, experts in BIM and SBD. The resulting process serves as a route where the critical tasks and decisions in the process can be identified. The developed process is not meant to be prescriptive, but aims to raise considerations during the design process, and increase the understanding of sustainability, by making explicit what is currently tacit among SBD experts. These considerations can help prevent lost opportunities to maximise the building's performance by highlighting critical issues at specific stages along with the reasoning behind each decision. Once the description is completed, it will inform novice building practitioners, and raise their performance to a level comparable to that of an expert (Mayer et al., 1995).

3.5.1.2. BIM contractual agreements

Liability and ownership are significant concerns when it comes to collaborative BIM processes (Barnes and Davies, 2014). The role of the protocols and standards is the management of information, and the complex relationships between social and technical resources that represent the complexity, collaboration, and interrelationships of current organisational environment (Jernigan, 2008).

The legal aspects that have been associated with BIM implementation usually fall within three categories (Sackey, 2014): (i) risk and liability, (ii) ownership of information, and (iii) security and confidentiality. Therefore, defining the roles, responsibilities and information deliverables for each project participant, in a collaborative effort, becomes critical. This way, the management of complex work processes and large amount of information are easier to track (Sebastian, 2010). The inefficiencies of current contracts to address the above issues have been stressed in the literature (Fischer and Kunz, 2004; Ghassemi and Becerik-Gerber, 2011). Collaborative contracts are suggested in order to implement IPD, partnering, and alliancing principles that are grounded on open communication, trust, and dispute avoidance (Sackey, 2014).

In the UK, a number of legal documents have been developed for BIM collaboration such as the "*CIC BIM Protocol*", "*CIC Best Practice Guide for Professional Indemnity Insurance when using BIM*", and "*CIC Outline Scope of Service for the Role of*

Information Management" (Construction Industry Council, 2013). Al-Shammari (2014) has evaluated the CIC Protocol as being too difficult to control and "*too process driven*" as a considerable amount of work is necessary to fill the appendices of the protocol. This process could be streamlined by following an automated approach to the scoping of the project. Moreover, Gibbs et al. (2015) have identified the deficiencies in the CIOB's "*Complex Projects Contract*" (2013), which focuses on the virtual model rather than the collaborative working process. What is more, the contract focuses on the relationship between the client and the contractor, neglecting the rest of the project team members. The literature's consensus is that contractual arrangements need to be re-examined to accommodate BIM collaboration (Kumaraswamy et al., 2005). For high performance buildings, Homayouni (2015) has identified contractual, organizational, and social elements, and has proposed typologies for the incorporation of BIM into working processes.

Although the publications discussed above provide valuable guidelines for BIM implementation, the roles of the sustainability specialists, who are essential to the process, remain bespoke and ill-defined. Therefore, the value and contribution of these roles need to be clarified and acknowledged. These definitions can potentially be used into formal contractual agreements so that the responsible parties are compensated for their services.

3.5.2. Technology field

This Section examines the technological enablers of BIM–enabled collaboration for SBD. The main issues discussed are software capabilities and interoperability between applications as well as collaboration platforms that enable the exchange of design deliverables. Levy (2011) has distinguished the types of software applications based on their functionalities as: architectural design, structural analysis, MEP, BPA and assessment, coordination (e.g. Autodesk Navisworks, Solibri Model Checker), and construction management. Nevertheless, all the above pieces of software are considered BIM, since the core of BIM is information management and its philosophy is about integration.

The use of varying software types, aligns with the notion that the evaluation process of a project should not be seen as a simple linear process, since it follows a cyclic nature (Bentivegna et al., 2002; Ding, 2008). However, changing workflows and integrating technology is a change management process. Defining clearly the expectations for each step will make it possible for the entire team to work in concert to make changes to their business, effectively and efficiently (Jernigan, 2008). Designers of tomorrow will be able to access rich sets of real-time facilities data, and will use rules-based systems to eliminate most of the repetitive work. Systems that link business decision-making directly to the design process will be the norm. Current technological options offer a unique opportunity for predicting how a real structure will perform, but to practically implement BIM, it requires re-thinking of the traditional methods of designing (Garber, 2009).

3.5.2.1. BIM and BPA software tools

The most popular drawing tools, in the UK construction industry, have been explored in the NBS National BIM Reports (NBS, 2015b; NBS, 2016). Furthermore, a list of certified BIM software versions has been published by buildingSMART (2012). Architectural designing for performance requires quantitative data, and as a result, BIM is the adequate tool to utilise for this purpose (Dowsett and Harty, 2013; Levy, 2011). Construction professionals utilise BPA tools to predict, and quantify, aspects of sustainability from the early design stages so as to significantly ameliorate both quality and cost during a building's life cycle (Becker, 2008; Cole, 2005; McGraw-Hill Construction, 2010; Eastman et al., 2011). According to De Wit and Augenbroe (2002), environmental assessment is most efficient during the identification and preparation stages of a proposed project. The most comprehensive list of building energy software tools is presented in the BEST (Building Energy Software Tools) directory (formerly hosted by the US Department of Energy, DOE).

Krygiel and Nies (2008) indicate that BIM can aid in the following aspects of SBD: (i) building orientation (selecting a good orientation can reduce energy costs), (ii) building massing (to analyse building form and optimise the building envelope), (iii) daylighting analysis, (iv) water harvesting (reducing water needs in a building), (v) energy modelling (reducing energy needs and analysing renewable energy options can contribute to low energy costs), (vi) sustainable materials (reducing material needs and using recycled materials), (vii) site and logistics management (to reduce waste and carbon footprints). Attia et al. (2013) have identified the objectives that the BPA software attempts to optimise when performing sensitivity analysis: (i) building layout and form, (ii) geometry, position, and window to wall ratio, (iii) building envelope, (iv) daylighting performance considering automated control of solar shadings, (iv) natural ventilation strategies, (v) shape and functional structure of buildings as well as heat source utilization; (vi) HVAC systems sizing, (vii) HVAC system control parameters and/or strategy, (viii) thermal comfort, (ix) HVAC system configuration synthesis, (x) managing of energy storage and automated model calibration, (xi) simultaneous optimization of building envelope and HVAC elements, (xii) simultaneous optimization of building construction, HVAC system size, and system supervisory control, and (xiii) simultaneous optimization of building construction, and HVAC.

Nonetheless, complexity among BPA tools varies significantly; for example, there are dynamic performance simulation tools (e.g. Integrated Environmental Solutions Virtual Environment, IES-VE) that model the time varying behaviour of a system, and there are spreadsheets (e.g. PassivHaus Planning Package, PHPP) that perform calculations utilising steady state conditions. The former give more accurate estimation of the building's environmental performance than the latter but they require more processing power, and time, to perform the simulation. It is preferable that those tools are utilised in conjunction with each other to utilise the different strengths dependent on the purpose of the estimation and the stage of design. Therefore, several studies have recommended that the users have to consider adopting a variety of tools, which would support a wider range of simulations that a single tool cannot offer due to the lack of extensiveness (Attia et al., 2009; Crawley et al., 2008). It has been emphasised that the selection of the most appropriate software is extremely important in order to streamline the working process and achieve doing more with less effort (Smith and Tardif, 2012; Tudor, 2013). If a building model offers limited analysis options, or is too restrictive, ultimately is not useful for affecting decision-making (Brahme et al., 2001). The questions that designers should consider regarding a software tool fall within the categories of ease of use, time and cost, interoperability, input, output, and accuracy (AIA, 2012; Yezioro et al., 2008). Despite the proven benefits of these tools (Attia et al., 2009; Azhar et al., 2011; Brahme et al., 2001; Çetiner, 2010; Ding, 2008; Gerber et al., 2012; Geyer, 2012; Mourshed et al., 2003; Parasonis et al., 2012; Schlueter and Thesseling, 2009; Stumpf et al., 2009), their practice should be utilised with careful consideration of the information requirements and the expected outputs of certain types of analysis. BIM software addresses this issue by promoting the integration of multidisciplinary information, and thus, presents an opportunity to use accurate inputs to perform BPA. As a result, the probability of achieving more reliable outputs is increased. The capabilities of several BPA software tools have been summarised in a paper presented in the *Sustainable Building and Construction Conference (SB13)* at Coventry University in July 2013 (see Appendix A).

The reliability of the BPA software is tested using validation techniques. The importance of validating modelling capacity, input-output style, extend of built-in databases, speed of simulation and accuracy of results has been discussed in the *"closing the gap"* report (Lomas et al., 1997). The two main validation methodologies utilised are empirical validation, and inter-programme comparison (Strachan et al., 2008). Inter-programme validation is done either by physical calculation or by statistic calculation. Physical calculation makes a precise calculation of detailed tasks as well as overall energy consumption. Statistic calculation models are simplified for the estimation of total energy, heating or lighting demand (Schlueter and Thesseling, 2009). Other validation tests are the CIBSE TM33 (CIBSE, 2006b) for software accreditation and verification, and the ASHRAE (American Society of Heating, Refrigerating, and Air-Conditioning Engineers) Standard 140-2007 (ANSI/ASHRAE, 2011) methodology, which allows different building energy simulation programs by representing different degrees of modelling complexity to be compared with other energy program's predictions. However, not every BPA tool is compliant with the National Calculation Method (NCM); the list of tools that include this option has been published by the UK Government (2014). Furthermore, this practice requires changes in the modelling methods according to the NCM modelling guidelines (EPBD-NCM, 2014).

It has been recommended that energy modelling should provide design teams and owners with continuous feedback throughout the design process (AIA, 2012). Therefore, IPD suggests that a BPA specialist is involved at every decision so as to suggest opportunities for improvement. AIA's "*An Architect's Guide to Integrating Energy Modelling in the Design Process*" (AIA, 2012) outlines the team goals, energy modelling goals, and the benefits to the client, but it does not give indication concerning the interrelationships between project participants and their influence in the end goal. It has been discussed that the obstacles in the use of BIM are (Yudelson, 2008): (i) the blunt nature of the current tools, and the perception that existing tools are easier to use; (ii) the lack of knowledge about the availability, and capabilities of the tools as well as been intimidated to use them. It is believed that informing and educating people about the availability of options and their use will help them understand and implement the new technology.

3.5.2.2. Interoperability standards and methods

A major enabler to achieve integration of sustainability assessment within BIM collaboration is interoperability. "*Interoperability is the ability to exchange data between applications, which smoothes workflows and sometimes facilitates automation*" (Eastman et al., 2011). This definition expounds the central role of interoperability to BIM processes as it enables users of different platforms to seamlessly offer an input into a common model. The importance of interoperability is that it has the potential to bring standardisation in the construction industry (Grilo and Jardim-Goncalves, 2010). The vision for the future is that fully Web-enabled transparent information exchanges will be practiced.

For that purpose, the global AEC/O and FM industry has been striving to achieve data interoperability for the last twenty years (Laakso and Kiviniemi, 2011). The two major interoperability standards are buildingSMART's IFC, a common data scheme that allows interoperability across software packages (buildingSMART, 2012), and the COBie (East, 2014), which denotes how information may be captured during design and construction, and provided to facility operators (Charalambous et al., 2011). COBie format is the interoperability standard that is part of the defined requirement for the Level 2 BIM data drops (BSI, 2007). The purpose of the COBie delivery schema is robust information organisation for FM in an open exchange format (East, 2014; Cabinet Office, 2011). It is a spreadsheet data format for the publication of a subset of building model information focused on delivering building information (rather than geometric modelling), such as equipment lists, product data sheets, warranties, spare parts lists, preventive maintenance schedules, and so on. Other developed standards include: buildingSMART Data Dictionary (bSDD, former International Framework for Dictionaries), and Information Delivery Manual (IDM), and XML (eXtensible Markup Language) schemas (e.g. OpenGIS, ifcXML, agcXML, CityXML). Moreover, the IFC schema is possible to be transformed to implement energy simulations (Hitchcock and Wong, 2011). It has been proven that using the IFC format is the way forward for BIM maturity since proprietary formats will always diverge (Howard and Björk, 2008; NBS, 2012). Ahn et al. (2014) have developed an automated IFC based model for transferring geometric and thermal properties to EnergyPlus but a complete simulation model has been found to be "*difficult to make*". A number of schemas have been developed for extracting the environmental data in a neutral format so as to facilitate integration (e.g. gbXML, ecoXML, IFCXML, greenbuildingXML, and ecoXML).

BPA tools enable the user to import information from BIM through open standards, and as a result, collaboration workflows need to be reinvented. However, a common problem of implementation is the alignment of information requirements (Kota et al., 2014). Another limitation of the BPA software tools is that they provide simplified versions of the building, and thus, their computational algorithms are not able to cope with BIM complexity (Svetel et al., 2014). Another option for BPA is the built-in applications; these tools are embedded into BIM software so that the process of transferring the data to the simulation engine, and back to the BIM model, takes place in the background. An example of such application is Energy Evaluation in ArchiCAD 17. Autodesk has also developed a number of plugins for different types of sustainability analysis within Revit 2015. The main advantage of this approach is quick feedback to the designer at the inception and early concept stages of design. Table 3.1 shows the sustainability analysis capabilities that are either built-in by default, or can be embedded by plug-in into Revit 2015.

Table 3.1 Sustainability Analysis embedded in Revit 2015

Sustainability Analysis	**Default in Revit and/or Revit Plug-in (link)**
Parametric and computational design	Dynamo for Revit (http://dynamobim.com/)
Energy modelling	Revit (built-in)
Wind analysis	Flow Design for Revit (http://www.autodesk.com/education/free-software/flow-design)
Climate analysis	Revit (built-in)
Daylight and electric lighting analysis	Lighting Analysis for Revit (http://www.autodesk.com/products/lighting-analysis-revit/overview)
Whole building energy analysis	Revit (http://www.autodesk.com/products/energy-analysis-revit/overview)
Solar studies	Built-in in Revit, and plugin on Labs (https://beta.autodesk.com/callout/?callid=A85F5FB11247411E985ED97605743273)

3.5.2.3. Information Communication Technology (ICT)

ICT is a broader term used for computer and network hardware and software. Despite the proven benefits of ICT for collaborative design (Adamu et al., 2015; Childs et al., 2014; Ruikar et al., 2005), their adoption remains low. One possible reason is because the companies that have invested in ICT have neglected peoples' issues such as communication education, training, and management of change (Damodaran and Shelbourn, 2006). In the case of high performance buildings, the need for coordinating a larger amount of information from a wider range of participants, apart from the core disciplines, increases significantly. This integration requires attributes such as early involvement of participants, team experience, levels and methods of communication, and compatibility within project teams (Nofera and Korkmaz, 2010). Efficient team communication, results in collective working that enhances the individual understanding of design needs (Otter and Emmitt, 2008). Pala and

Bouchlaghem (2012) have argued that ICT could enable SBD collaborative processes "*only if the design managers employ a structured, systematic approach to manage the assessment".*

Several researchers have examined the requirements for effective collaboration utilising ICT. Singh et al. (2011) have defined the technical requirements for a BIM-server (as a collaboration platform): (i) BIM model management-related, (ii) design review-related, (iii) data security-related, and (iv) BIM-server setup, implementation and usage assisting. Bouchlaghem et al. (2005) have defined the following eight functional components: (i) user interface, (ii) client briefing tool, (iii) cost modelling tool, (iv) constraints checking tool, (v) risk assessment tool, (vi) sketching and drawing tool, (vii) 3D visualization tool, and (viii) synchronous and asynchronous communication tool. Moreover, Lutzendorf and Lorenz (2006) have claimed that for ICT tools to be utilised for sustainability, they need to be: (i) readily available, (ii) documented and explained sufficiently, (iii) user-friendly and able to deliver easily interpretable results, (iv) provide education and training to the users, (v) capable to refer to case studies for optimisation of design, (vi) able to generate documents and reports, (vii) adjustable to the users' working methods, and (viii) capable of processing design information generated for the different design stages.

Planning and Implementation of Effective Collaborative Working in Construction (PIECC) framework (Shelbourn et al., 2007) has strived to enable organisations to fully integrate ICT, as well as the associated people and business issues, in their projects. The components of the PIECC framework are processes, standards and protocols, and tools. Sheriff (ibid.), building on the PIECC framework, has developed three information management frameworks for collaboration with each having different focus. Bouchlaghem (2012) has emphasised the need to critically analyse processes in order to understand information needs so as to suggest solutions grounded on stakeholders' requirements.

Tarandi (2013) has developed a framework for a BIM repository called "*sustainable urban collaboration hub*" for structuring information and processes in the construction industry. Cheng and Das (2014) have presented a framework for a cloud-based BIM server that facilitates information exchanges using open BIM standards. Jrade and Jalaei (2013) have developed a model for SBD building projects at conceptual stage to address links with material databases and interoperability with simulation tools. Nonetheless, what is missing from the above efforts is the planning functionality for collaborative SBD. Furthermore, the definitions of tasks, and rules along with the how-to knowledge have not been sufficiently addressed yet.

The processing power of computers, server capacity, networks and internet connection are additional aspects that need to be considered to achieve integration. The existing technological maturity creates the need to rethink and redesign the traditional collaborative processes so as to enhance the centrality of information and exploit the potential benefits of mobilisation and cloud computing. The use of this new technology will help transform the current perception of the industry by enabling the mapping of the collaborative processes, and thus, leading to the future IPD approach. A number of CDE solutions are available in the market today, offering a great variety of capabilities. However, none of these platforms has sustainability considerations integrated within it. Thus, what is currently lacking to enable BIM collaborative SBD is a well-defined structured process for its implementation. It has been argued that, better understanding of communications and semiotics could lead to better BIM technologies (Cerovsek, 2011).

3.5.3. Process field

It has been noted that BIM is above all a process; one that will be regularly used in the UK construction industry in the years to come (Barnes and Davies, 2014). Within this process, sustainability should be integrated from the beginning of design in order to be effective (Kaatz et al., 2006). Furthermore, the key design decisions that arise at the early stages need to be based on the appropriate information (Thomson et al., 2009). For this reason, this Section discusses the elements that form the SBD process. Those include people, and their roles and responsibilities, along with the artefacts that consist of the information exchanges, and their components. It has been proven that effective collaboration does not result solely by the implementation of information technology solutions; organisational and people issues need to be resolved as well (Bouchlaghem, 2012). It is argued that repeatable processes can be standardised in order to streamline the design process. As a result, the automation of repeatable processes is important for collaborative design (De Vreede and Briggs, 2005). The world is moving from a hierarchical (command and control) to a distributed (share and collaborate) model (Jernigan, 2008). Especially for performance-based design, communication is the main issue (Bakens et al., 2005) due to increased complexity, and amount of specialisation.

It has been found that the successful implementation of collaboration systems depends 80% on tackling with people and process issues, and only 20% on resolving technology aspects (Wilkinson, 2005). The resistance to technology has two broad areas: (i) principle of collaborative working, and (ii) the adoption of the technology itself. Successful collaboration requires a combination of people, processes, and technologies, but people is the most difficult to get right. This is why it has been claimed that technology has evolved faster than people have (Jernigan, 2008). Thus, there is the need to retool social cultures in the building world to catch up and take advantage of the existing workforce. Integrating technology does not require that architects throw away all their proven tools and experiences (Jernigan, 2008). It does, however, require them to look at things differently; it requires them to separate the things that should be kept from those that should be replaced. With integrated practice, architects become better designers, and more valuable to their clients (Jernigan, 2008). The most important issue remains; people need to learn how to share more so that they can move from "*creative isolation*" to meaningful collaboration assisted by the new technology. This can only be achieved by changing the existing individual working patterns (Wilkinson, 2005). To overcome fragmentation, the 4 Es method has been suggested (Yudelson, 2008): Engage Everyone Early with Every issue. For SBD, the project team expands significantly, along with the interdependencies between team members' tasks and deliverables. A workflow management system that enables tracking of information and automatic updates can assist in engaging the appropriate stakeholders timely throughout the design process. It is supported that a rules-based system can codify the knowledge about any subject (Jernigan, 2008), and thus, sustainability. By defining how these bits of knowledge interact, most fact-based assessments that drive planning can be automated.

3.5.3.1. Design participants and roles

Historically, builders were the master masons in charge of a craft-based project, often designing as they go. An important historical point is that organisation and management was very much simpler prior to industrialisation because there were few interfaces between trades and skills (Hughes and Murdoch, 2001). After that, the increased amount of specialisation made management more complex. Since then, it has been the architect that has been leading the design team (Sinclair, 2011). After that, the role of the project manager has emerged. The crucial issue of project management is to identify the stakeholders who can affect the project and understand the demands from its conception (Olander and Landin, 2005). For BIM implementation, the focus shifts from architect-process to client-process. The client's role is crucial to set goals from the start, clarify expectations, and employ the appropriate people. Nowadays, researchers have recognised the need for better management of the SBD process (Delnavaz, 2012; Rekola et al., 2012). To achieve that, a common language for job titles, descriptions, and responsibilities, should be adopted (Green Building Education Services, 2011). Wang and Huang (2006) have stressed the fact that the stakeholders' project performance positively correlates with each other. This fact is critical because for the SBD process to be successful, all of its elements need to perform at their best. Although a number of studies have noted that building design is a multidisciplinary process that requires contribution from a wide range of specialists, the AEC/O industry is hampered by fragmentation (Bouchlaghem et al., 2005; Charalambous et al., 2012; Sinclair, 2013), resulting in poor out-turn performance, and the need for extensive modifications afterwards.

It is argued that stakeholder identification for a specific system is a significant part of the process (Sharp et al., 1999). For the UK construction projects, the roles and responsibilities have been defined by the CIC Scope of Services (2007). However, the responsibilities of the design roles towards sustainability are not stated; they remain ad hoc and are not considered as an integral part of the process. The RIBA Job Book

(9th edition) (2013), that accompanies the RIBA Plan of Work 2013, has only defined four roles for concept design (stage 2): the cost consultant, structural engineer, building services engineer, and health and safety engineer. Moreover, essential roles for SBD implementation are neither mentioned in the *"Assembling a Collaborative Project Team"* guide (Sinclair, 2013); the "*project roles*" tables remain generic, and sustainability issues have not been adequately defined. Furthermore, Barlow's (2011) *"Guide to BREEAM"* has not defined any roles for SBD apart from the architects', the structural Engineers', and the quantity surveyors' responsibilities for BREEAM assessment. In addition, Hardin (2009) has defined the EIR, as an information exchange plan, only for the disciplines of the architect, contractor, and MEP and structural engineers. The NBS BIM Toolkit (NBS, 2015a) provides a way to define roles and responsibilities for bespoke projects, offering more flexibility for including them in the EIR, from the briefing stage of the design process onwards (BSI, 2013b; RIBA, 2013b). In spite of that, specialised roles and responsibilities for SBD remain ad hoc, and are not discussed in the literature.

So as to achieve integrated design for a sustainable building outcome, new design roles need to be considered apart from the traditionally involved participants. An example of such a role is the BIM model manager (RIBA, 2012). Additional new roles include the BIM information manager, BIM coordinator, BPA specialist, and sustainability consultant. The responsibilities for SBD can be fulfilled either by the core disciplines, if they acquire the skills and knowledge required, or by specialist subcontractors. As such, certain levels of BPA are relevant to the types of questions that need to be asked, and answered, by the architects (Brahme et al., 2001). Thus, in order to move towards the future of collaborative SBD, the traditional roles need to be redefined and changed. Furthermore, specialised roles that are related to SBD performance need to be clarified and understood (Green Building Education Services, 2011).

Despite the various procurement routes, there are two main team structures (Sinclair, 2013): (i) traditional project team, where a client appoints a design team that develops a certain level of detail to the project. Then, a number of contactors tender for the project; and (ii) contractor-led, where the project team is led by the contractor and the design team is part of the contractor's team. In that case, the contractors bid based on a comprehensive brief. This means that currently, the architect does not necessarily lead the project team, and that the timing of the contractor's involvement varies. Furthermore, various sub-contractors are responsible for many aspects of design. Therefore, planning is crucial in order to achieve the best possible start at a project. The "*Who, What, When, and How*" aspects should be considered holistically and "*can be utilised on every project"* (Sinclair, 2013). This claim suggests that certain repeatable processes can also be standardised, and automated. However, the "*Why*" aspects have been considered as individual for each project. This research accepts that the above mentioned elements follow repeatable processes, but flexibility and adaptability is also essential due to the bespoke nature of construction projects. Thus, the requirements of BIM-enabled SBD implementation need a better definition, one that is not restrictive.

3.5.3.2. Design artefacts and components

BIM processes require digital information, typically, that is the documentation exchanged between parties as CAD and PDF files (Hardin, 2009). For BIM-enabled collaboration, the format as well as the content of the information exchanges need a clear definition so that they can be communicated amongst the design team to achieve common goals based on transparency. Whyte and Lobo (2010) have distinguished digital artefacts into: (i) object geometries (e.g. drawings, simulations and other, that represent physical realities), (ii) standardised formats (for structuring and distribution of digital datasets), and (iii) repositories (for storage and transfer of catalogued objects). Levy (2011) has described the BIM artefacts of communication as the following: (i) photorealistic rendering, (ii) 3D viewable model, (iii) 2D/3D vector geometry, (iv) energy and modelling analysis, (v) BIM compatible IFC model, (vi) BIM component library and database, (vii) text reports and schedules, and (viii) walkthrough/flyover animations. This research study acknowledges that construction technological artefacts do not exist in isolation (Whyte and Levitt, 2011). Thus, the effective coordination between software, hardware, and data is essential for project success. Furthermore, it should be targeted according to the set goals of each project. Another important issue is the transformation of the data into formats that enable their retrieval by multiple users for different scopes (Bazjanac and Kiviniemi, 2007). A CDE can potentially automate this process by performing the appropriate transformations, depending on the role of each user in the design process.

The importance of a Design Responsibility Matrix (DRM), as a key tool for project development, along with Defined Deliverables (DD) is argued. For that purpose, the Level of Detail (LOD) for geometric definition and Level of Information (LOI) for data definition concepts have emerged in order to manage the information exchanges more effectively. In BIM execution planning, the LODs are critical because they represent the information included in the model at specific stages and are associated with the practical side of BIM implementation (Wu and Issa, 2014). The definition of LODs as *"Level of Development"* has been published in the AIA E202 *"Building Information Modeling Protocol Exhibit"* (AIA, 2008), and updated in AIA's *G202-2013 Project Building Information Modeling Protocol* (AIA, 2013). In the UK, the PAS 1192-2:2013 has defined the LOD as "*Levels of model detail*" for graphical content, and LOI (Levels of model information) for non-graphical content (BSI, 2013b). RIBA has also introduced the Level of Design (LOD) in "*Assembling a Collaborative Project Team"* (Sinclair, 2013). When the BIM model contains the adequate amount of information at the early stages of design, the BPA become a routine by providing immediate feedback on design alternatives for informed decisions (Barnes and Davies, 2014). Leite et al. (2011) have argued that *"additional modelling effort can lead to more comprehensive analyses and better decision support during design and construction".* To this date, sustainability considerations have not been aligned with the existing LODs. This research attempts to provide the LOI requirements for SBD, which should be integrated with the LOD100 and LOD200 during the implementation of concept design.

In terms of content, the explicit knowledge (the what) is the knowledge that can be documented (Carrillo and Chinowsky, 2006). It refers to the building components that are captured in BIM, technical models, drawings, and specifications. Tacit knowledge (the why) is the knowledge that people acquire from experience (ibid.). Parts of this knowledge can be documented as well, for repeatable processes, so that they form the rules and justifications of the process. However, in the current BIM processes, the "*how-to*" has not being defined, and there is no method to facilitate the above suggestions. It is argued that the embodiment of the IPD theories is currently missing for SBD. The developed concept should take account of the whole spectrum of policy, technology, and process aspects. Therefore, fragmented approaches cannot facilitate the use of BIM; a holistic approach to information management is essential. For this reason, both bottom-up and top-down perspectives are equally important for organising the SBD process. It is suggested that, a defined process will permit the replication of lessons learnt from existing projects into future ones. Thus, this research attempts to formalise the lessons learnt from the best practices so that it can be used to inform the design of future buildings. Nevertheless, the developed process should not be prescriptive so as not to hinder innovation. The development of a standardised process for scoping sustainability roles, responsibilities, outcomes, and deliverables would result in critical outcomes such as (Kaatz et al., 2006): (i) improved integration of sustainable principles, and stakeholders' values and knowledge; (ii) improved transparency and accessibility to information; and (iii) better communication, collaborative learning, and transfer of knowledge.

3.6. Synergies between BIM and sustainability

Recent research studies have resulted in producing conceptual frameworks to test interoperability and capabilities of common simulation tools (Azhar et al., 2011; Barnes and Castro-Lacouture, 2009; Bazjanac, 2008; Che et al., 2010; Hamza and Horne, 2007; Hetherington et al., 2011; Lee et al., 2007; Magent et al., 2010; Maile et al., 2007). Some BIM related frameworks are also based on the international assessment rating systems (Biswas and Wang, 2008; Biswas et al., 2009; Ghosh et al., 2011; Lützkendorf and Lorenz, 2006; Nofera and Korkmaz, 2010; Sinou and Kyvelou, 2006; Wong and Fan, 2013), and regulations (Kasim, 2015; Cardiff University, 2007). Others have created tools that are integrated into BIM to automate performance based decision-making (Brahme et al., 2001; Feng et al., 2012; Huber et al., 2011; Schlueter and Thesseling, 2009; Welle et al., 2011). However, organisational aspects of BIM-enabled SBD have not been addressed sufficiently in the literature.

The Centre for Integrated Facility Engineering (CIFE) of Stanford University has published a detailed report (TermalOpt) for BIM-based thermal multidisciplinary design optimisation (Welle et al., 2011). They have also created plugins to existing simulation tools for data conversion for thermal and daylight analysis. This method offers a lot of accuracy in the analysis of complex geometries, but requires expert knowledge and specialisation for the use and interpretation of results of the BPA software (e.g. EnergyPlus, Radiance). Still, the framework does not address any organisational aspects of SBD. Design4Energy project is also developing a collaboration platform, which focuses on increasing the energy efficiency of buildings by allowing the creation of evolutionary scenarios. Furthermore, process mapping techniques have been utilised to map design workflows (Design4Energy, 2013).

Barnes and Castro-Lacouture (2009) have created an embedded tool into Revit Architecture 2009, for LEED automation, acknowledging the advantage of the use of consistent information from the BIM model, while Biswas et al. (2009) have mapped the system requirements to elements of the BIM model for decision-making. Wong and Kuan (2014) have developed a framework for the BIM-based implementation of BEAM Plus. Jrade and Jalaei (2013) have worked on the integration of BIM with rating systems (e.g. LEED). Azhar et al. (2011) have also proposed a framework for sustainable design and LEED rating analysis. This framework has also tested the interoperability and capabilities of commonly used simulation tools (e.g. Ecotect, IES-VE) to predict LEED credits. Kasim et al. (2012) have pursued regulatory compliance assistance and BIM-enabled compliance with the BREEAM rating system. Similarly, Ilhan and Yaman (2016) have developed a "*green building assessment tool*" for the generation of documentation for obtaining BREEAM certification. None of these efforts have attempted to define the collaborative process to provide guidance for SBD implementation and delivery.

Schlueter and Thesseling (2009) have suggested an embedded (into Revit Architecture 2008) tool, for the instantaneous energy and exergy calculations, based on statistic calculation models rather than physical models. The advantage of this choice is that simulation lasts for seconds instead of hours. For early conceptual design, this can be a preferable approach since other simulation tools may provide the illusion of accuracy in their results, which is not a realistic assumption when many design parameters remain still unknown. Bank et al. (2010) have presented a decision-making tool that is linked to BIM software. The tool assesses trade-off analysis using actual building characteristics, based on either sustainability indicators or building rating systems, acknowledging the importance of subjective prioritisation of objectives in the design process. As a result, this SBD method allows un-connected analyses to be integrated in a systemic fashion to a finite budget (Bank et al., 2010). Geyer (2012) has suggested a parametric system modelling method for decision-making based on system engineering. However, systems perspective has limited capabilities for complex geometry dependencies, and works better for non-geometric interdependencies. This simplification is rather crude considering that the shape of the building plays a significant role in its environmental performance (Parasonis et al., 2012). Gerber and Lin (2014) have created a plug-in for Revit to integrate a prototype tool (H.D.S. Beagle) that performs parametric and trade-off analysis. The prototype results in a broader based design solution pool with no consideration of aesthetical aspects or other qualitative design criteria.

Based on a methodology for IFC-based semi-automated building energy performance simulation (Bazjanac, 2008), Gupta et al. (2014) have suggested a framework, and a stand-alone tool, for solar PV simulation using an open exchange standard. The tool uses the information in the IFC format as central data model, and is also partially linked to information repositories. The advantage of this approach is that it offers flexibility in the use of a variety of IFC compliant tools. Chou and Ongkowijoyo (2014) have created a model for analysing group decision-making regarding renewable energy policy selection. They have combined graphical matrix approach with Monte Carlo simulation to compare alternative schemes by a set of defined performance indicators so as to address uncertainty in attribute comparisons by expert panels. This way, the study has implemented a risk-based technique that probabilistically represents expert judgment. Oti and Tizani (2015) have developed a prototype decision-support algorithm for the sustainability appraisal of concept steel design. This attempt has focused on the implementation of BIM by civil engineers and no interactions between stakeholders are considered. The above mentioned approaches are useful but facilitate "*lonely*", Level 1, BIM maturity. Sanguinetti et al. (2012) have presented a method for integrating design analyses in BIM. However, the process diagram developed has not distinguished the responsibilities that different stakeholders have towards sustainability, and the roles' definition is limited to "*designers*". Kota et al. (2014) have facilitated daylight simulation and analysis automation. Cheng and Das (2014) have developed a framework for BIM-based energy simulation and code checking. The framework has suggested automated energy simulation, utilising the EnergyPlus engine.

To date, there is no method, or tool, that assists the planning and definition of the SBD process. The above efforts have been missing a crucial step; that is the scoping and planning of the project. Akbarnezhad at al. (2014) have suggested a process-centric approach for integrating the model database with a data input database for deconstruction strategies and integration with BIM. However, there is no consideration for planning and responsibilities, and no management functionality. Motawa and Carter (2013) have developed a systematic methodology for monitoring performance of buildings. Lu and Olofsson (2014) have used process mapping of interdependencies between planned construction tasks. Other studies have focused on quality management for BIM (Chen and Luo, 2014), and quality, safety, and carbon emission management based on the BIM model (Ding et al., 2014). Magent et al. (2010) have proposed a design process evaluation method that attempted to: (i) identify critical decisions in the design process, (ii) evaluate the decisions for time and sequence, (iii) define the information required from various stakeholders, and (iv) identify stakeholder competencies for process implementation. It has resulted in a definition of the optimum decision-timing equivalent to the point at which the marginal benefit of making the decision is equal to the marginal cost of waiting to make the decision.

It has been proven that managerial issues in construction information systems are more influencing than technology issues (Jung and Kang, 2007), but very little is known about how these decisions are made in order to steer the design process (Cerovsek, 2011; Jung and Joo, 2011; Zerjav et al., 2013). Although a significant body of research has been conducted on topics related to BIM-aided collaborative design, and the efficient use of BIM technology, little is known about the incorporation of BPA into these processes. This study argues that technical approaches are bound to fail without changes in the organisational structures. Most of the above efforts, although they utilise BIM software, are "*Lonely BIM*" attempts for SBD, assuming that collaboration is pre-existent, or defined. This is the main objective of process modelling; to provide designers with high quality information on which to base their decisions (Dorador and Young, 2000). Evidently, the main problems for BPA are the accuracy of tools, and the data flows (Motawa and Carter, 2013). Thus, it has been supported that the most important part of IPD is being very clear and focused on what the answer must be, and then, develop a process to get there (Yudelson, 2008). Ideally, the process, IT, people, culture, and customer level need to be considered, and developed, together in order to produce a comprehensive model (Cooper et al., 2008). It has been found that the critical dimensions of IT involvement are simulation, integration, communication, intelligence, visualisation, and IT support. Therefore, the main problem that is faced is the lack of coordination, and technological management of IT. The two dimensions in the fragmented design and construction process are (Sebastian, 2011): (i) process and IT alignment, and (ii) co-maturation of IT and processes needs. The adoption of BIM can address the above issues noted by Sebastian (2011): (i) enabling communication between disciplines; (ii) allowing for the early approximation of lifecycle analysis, and their elucidation to the client; and (iii) drawing/demanding contracts and delivery methods.

However, there is still no comprehensive and structured process to assist professionals for the planning and delivery of SBD from the early stages so as to harness the talents of all building professionals' disciplines, and achieve optimum results. Nevertheless, the importance of incorporating all disciplines from the early stages of design is widely acknowledged and documented (Bouchlaghem et al., 2005), along with how crucial early decisions are in order to achieve sustainability in the resulting outcome (Schlueter and Thesseling, 2009). The RIBA Plan of Work 2013 (RIBA, 2013b) strives to address these issues, but sustainability aspirations are only limited to a checklist. This approach provides very little information concerning how sustainability can be integrated into the design process, and not be treated as an add-on. Design processes need to be developed to their next level of refinement so that they become clear and established methods for setting out how many parties can work in the same model environment at the same time (RIBA, 2012).

3.7. Summary

The comprehensive review of literature, presented in this Chapter, suggests that BIM is considered to be the future of collaborative building design. However, there is confusion about what it is and how it should be utilised and implemented. Despite the fact that using its 3D capability to produce visualisations is increasingly becoming adopted, its true (nD) potential to manage information is not yet exploited (NBS, 2015b; NBS, 2016). What drives an integrated practice is a collaborative process where the value of team members is recognised, and utilised, to achieve the client's goals. It has also been justified that sustainability issues should be considered as early as possible in the selection phase so as to minimise environmental damage, maximise the return to natural resources, and reduce remedial costs. BIM combined with a range of BPA software that support interoperability standards can manage a building's lifecycle performance. However, a dynamic procedure is essential in order to assess, and re-assess, sustainability considerations during the SBD process iteratively. So as to make one step forward towards sustainable development, assisted by the new technological improvements (software, hardware, and networks), and adapt to this technological evolution, there is the need to specify the process of BPA within BIM-collaboration. The challenge that this incorporation faces is the effective orchestration, and coordination, of the available elements, which are necessary to achieve optimum results. To achieve a SBD process, critical decisions should be considered timely in order to assess trade-off relationships between specialised disciplines with varying aspirations.

The need for a structured collaborative SBD process that assists coordination between building professionals so as to utilise technology capabilities, and improve sustainable outcomes through common objectives, has been argued. Therefore, the purpose of this research is to develop a process model, and identify critical actions in the SBD process along with the LOI and the LOD that is associated to make a decision on an accurate basis. The goal is to make explicit what is currently tacit among SBD experts, and increase understanding of the implications of certain design decisions at the overall design outcome. It is believed that learning from experience can facilitate the scope of creating a more detailed process that advises future projects, and assists in preventing failures. This holistic systematic approach to SBD should combine both top-down and bottom-up strategies in order to tackle people issues (e.g. resistance to change), process issues (e.g. re-engineering approaches), and information management (data driven) approaches. The main literature findings, discussed in this Chapter, are summarised in Table 3.2.

Table 3.2 Key literature review findings of Chapter 3

BIM management maturity stages	Low	Ad hoc unstructured processes for exchanging files and paper-based documents (Level 0)
	Medium	Defined file-based collaboration that follows standard guidelines (Level 1)
	High	Managed information exchanges and collaboration workflows coordinated within a CDE (Level 2)
BIM-enabled SBD implementation fields	Policy	Regulations, Standards, Guidelines, Contractual agreements, Policy makers (DTI, RIBA, BRE, CIC, CIOB, NBS, buildingSMART, ISO, CIBSE, RICS)
	Technology	Hardware, BIM and BPA software capabilities and interoperability, ICT, OCPs
	Process	Roles, Tasks, Deliverables, and Decision points, DPoW (EIR, BEP, Classification, LOD, LOI)
BIM and SBD synergies	Regulatory compliance	Automation of Building Regulations, BREEAM, Code for Sustainable Homes, and/or LEED credit checking
	Software interoperability	Data conversion for BPA, Automated IFC-based energy performance simulation
	Decision-making automation	Embedded energy calculations, Trade-off comparison of sustainability indicators, Parametric system modelling
	Organisational approach	Collaborative alliance of people, systems, business structures, and practices (IPD), Mapping of interdependencies between tasks and deliverables

Chapter 4

Research design and methodology

4.1. Introduction

This Chapter discusses the philosophical underpinnings of this research project (epistemology and theoretical perspective), which guide the methodology (strategy, or plan of action) and justify the methods (techniques and procedures) used (Creswell, 1994; Crotty, 1998). A paradigm represents the philosophy (or else worldview, lens) that defines the nature of the "*world*", and guides actions and decisions (Creswell and Miller, 2000; Guba and Lincoln, 1994). According to Guba and Lincoln (1994), a paradigm is a set of basic beliefs (or metaphysics) that deals with ultimates or first principles. A research philosophy consists of the following components (Scotland, 2012; Tuchman, 1994): ontology, epistemology, axiology, methodology, and methods.

The Chapter starts by presenting the theory of knowledge, or philosophy, which consists of the ontology, epistemology, and axiology (Section 4.2). Then, the approaches to reasoning are discussed (Section 4.3) followed by the research strategy (Section 4.4). The methods used to gather and analyse data are introduced in Section 4.5 (qualitative, quantitative, and mixed methods). Section 4.6 provides an overview of the modelling methods considered, and justifies the selection of the process modelling techniques implemented in this study. Section 4.7 contains a chronological description of the research design and process; discussing decisions that took place regarding data generation, management, and analysis as well as quality measures considered to ensure the validity and reliability of this research. Finally, a summary of the Chapter is provided in Section 4.8.

Figure 4.1 shows the "*nesting*" of methodological elements adapted by Saunders and Lewis (2000). The diagram illustrates the hierarchy of concepts presented, and rationalised, in this Chapter. The outside ring represents the highest level of understanding (philosophy). This Chapter unfolds the "*onion*" from the highest level of detail (philosophy) to the most detailed layer (techniques).

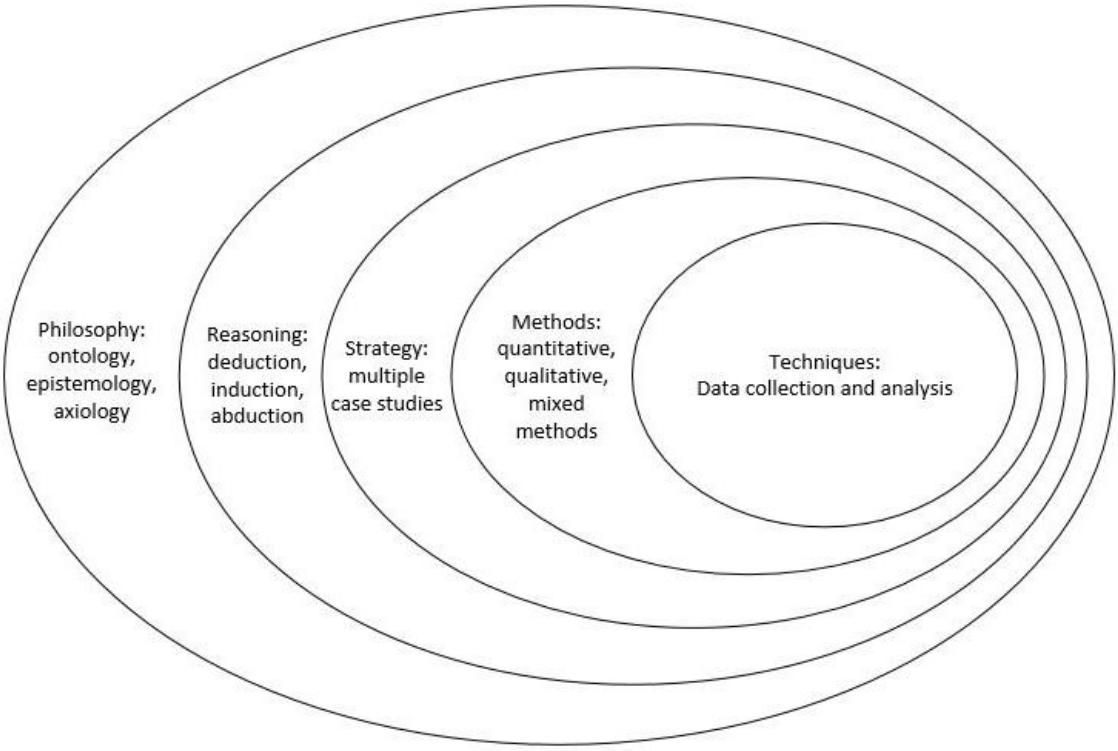


Figure 4.1 Nesting of methodological elements - research onion adaptation based on Saunders and Lewis (2000)

4.2. Research philosophy – theory of knowledge

This Section discusses the positioning of this research within the philosophical spectrum. Table 4.1 demonstrates a summary of the existing positions (i.e. paradigms). The ontological (objectivism vs nominalism), epistemological (positivism vs constructivism), and axiological considerations are presented in the following sub-Sections.

Table 4.1 Philosophical spectrum (Collins, 1983; Creswell, 2009; Crotty, 1998; Healy and Perry, 2000; Hyde, 2000; Lekka-Kowalik, 2010; Scotland, 2012)

	Paradigm		
Ontology (reality)	**Objectivism** (objects exist independent of perception)	**Relativism** (truth is dependent of consensus between viewpoints)	**Nominalism** (truth is dependent on the individual's perspective)
Epistemology (knowledge)	**Positivism** (explains causality - closed systems)	**Realism or Pragmatism** (no commitment towards a single system)	**Constructivism or Interpretivism** (studies individuals' social realities – open systems)
Axiology (values)	**Value-free or Value-neutral** (independent from influences)	**Value-laden or Value-driven** (influenced by social, ethical, and political values)	
Reasoning (logic)	**Deduction** (theory-testing, general to specific)	**Abduction** (combination)	**Induction** (theory-building, specific to general)
Methods (techniques and procedures)	**Quantitative** (can be measured)	**Mixed methods** (multi-methodology, complementarism)	**Qualitative** (based on description)

4.2.1. Ontology

Ontology is concerned with the nature of being and reality (Crotty, 1998; Scotland, 2012).

On one hand, Objectivism suggests that physical objects exist independent of perception. It can be used for the identification of laws so as to explain natural phenomena. While, in social research, Objectivism supports that social entities are objective realities and the truth is independent of individuals (Austin, 2009). In contrast, Nominalism suggests that the truth is dependent on the individuals' perspectives. Relativism is the view that reality is subjective and differs from person to person (Guba and Lincoln, 1994). Relativism also acknowledges that the truth is determined through consensus between different viewpoints, and so, what counts for truth can vary from place to place and time to time (Collins, 1983).

This research acknowledges that achieving sustainability is dependent upon how nature works, in terms of environmental design objectives. However, from an organisational perspective, the best Sustainable Building Design (SBD) process, is based upon how individuals perceive phenomena (individual perspectives), such as success or failure to achieve sustainability. Therefore, the experiences described in the interviews' narratives (provided during data collection), are dependent upon context, and no two things are exactly alike. The similarity of two events (scenarios) is an abstraction as interpreted by the researcher (Stiles, 1993).

4.2.2. Epistemology

Epistemology examines the sources and limits of knowledge, and the process of inquiring facts during research (Cohen et al., 2007).

On one end, Positivism recognises only observable phenomena, which is assumed to be driven by natural laws and mechanisms (Riege, 2003). This approach is mainly implemented for theory-testing during quantitative research such as experiments. On the other end, in Constructivism, which philosophical ideas are adopted in management and other social sciences, indicate a reality that is formed by the participants' perspectives that the world does not exist independently of our knowledge of it (Creswell, 2009; Scotland, 2012). The reality is constructed socially, and there is more than one reality (Charmaz, 2000). Thus, the research is dependent on time and context, and the people's perceptions are interpreted through the researcher's view of reality (Stiles, 1993). Moreover, the research questions have a more open-ended meaning, and the researcher is keen in listening carefully what the participant believes or analyses (Creswell, 2009; Easterby-Smith et al., 2008). The traditional view is that quantitative researchers subscribe to a Positivist paradigm of science, while qualitative researchers subscribe to a Interpretivism, or else Constructivism, paradigm (Hyde, 2000).

Pragmatists or Realists have no commitment towards any system of philosophy or reality, and they can use both qualitative and quantitative methods (Creswell, 2009). They believe that positivism is over-deterministic (in that there is little room for choice due to the causal nature of universal laws) and that constructivism is totally relativist (and hence highly contextual) (Flowers, 2009). The Realist alternative has been offered to overcome these limitations (Olsen, 2004). It supports that real structures exist independent of human consciousness, but that knowledge is socially created and is limited to our understanding, thus imperfect (Flowers, 2009). Realists research from different angles, and at multiple levels, that all contribute to understanding, since reality can exist on multiple levels (Chia, 2002). Therefore, Realism may be seen as inductive or theory-building process (Flowers, 2009).

This research follows the Realism or Pragmatism paradigm. The research problem itself is the main focus, and to achieve that, the researcher implements the approach (qualitative or quantitative), which is believed to best serve the needs of the research at each occasion. Case study strategy and in-depth interviewing methods, align with Realism theory-building research that emphasises on eliciting meaning rather than measurement (Healy and Perry, 2000).

4.2.3. Axiology

Axiology, the third component of the research philosophy, is classified based on whether the reality is value-free/value-neural, or value-laden/value-driven (Lekka-

Kowalik, 2010). Therefore, it is concerned with how individual values (social, ethical, and political) affect the research process and outcome.

The Objectivist paradigm ideal supports that scientific research is not influenced by any values. However, researchers argue that a value-free inference is not possible (Douglas, 2009). Especially, in Constructivism, or any type of theory-building research, the researcher is interactively engaging with the subjects of the study, thus his or her beliefs are influencing the inquiry. As a result, no-objective or value-neutral knowledge exists and all the claims that are made are relative to the values of the researcher (Riege, 2003). Furthermore, the participants' cultural background and values have an important effect on interview relationships (Knox and Burkard, 2009). Consequently, articulating ones values, and being aware of ones influences, means that the research is strengthened (Flowers, 2009). Several researchers advise the keeping of a reflexive journal during the research process (Henwood and Pidgeon, 1992; Lincoln and Guba, 1985; Ortlipp, 2008; Watt, 2007).

The researcher acknowledges that this research is not value-neutral. Therefore, reflexive journals have been kept to rationalise the research process and control biases, as much as possible. Parts of the journal contain summaries of literature excerpts, decisions undertaken, challenges, discoveries, and the evolving understanding of the researcher during this project. Initially, personal reasons have been the driver for this research; the researcher holds a strong conviction for environmental issues and sustainability, stemming from previously studying Energy Design at undergraduate level (5-year DipArch/MArch in Architectural Engineering), and further enhanced while attending the Environmental Design of Buildings MSc programme at Cardiff University (Welsh School of Architecture). Through these experiences, the researcher has been convinced regarding the importance of a holistic approach to the design of buildings prioritising sustainability. What was learnt thought this PhD project is the business aspect of SBD in terms of efficiency of the process (time, cost, and effort). What was a surprising realisation is the amount of inefficiencies that currently exist during the implementation of SBD in the UK. What is more, the biggest challenge was the identification and engagement of industry experts, since there are very few truly knowledgeable individuals that are associated with both SBD and BIM. The researcher's understanding is that the reason for having relatively low response rates is twofold; first, the uncertainty of participants regarding the area of research (stated by some during correspondence), and the reluctance of pioneers to share the expertise that gives them competitive advantage. Therefore, access to participants was more challenging than expected. On a personal level, the researcher understood the demands of qualitative research, which previously underestimated; designing, planning, and synthesising qualitative data, was significantly more complex, and time consuming, than initially anticipated. The reflexive journals have assisted in keeping an audit trail during this research. The most meaningful reflexions are included in Section 4.7 in more detail, where the chronological evolution of the research design process is presented.

4.3. Approaches to reasoning

This Section discusses the approaches to reasoning implemented in this research. The two traditional approaches to logic have been the deductive (top-down) and inductive (bottom-up) thinking (Skinner, 2010). Abduction is a more recent approach to reasoning, which combines both deductive and inductive steps (Schutt, 2011). The abductive approach, implemented in this research, has been systematically received and adopted during the past decades since it emerged (Ahmed et al., 2016; Bendassolli, 2013; Reichertz, 2007).

4.3.1. Deduction

Deduction has its roots in the ancient world, with Plato (428/427 or 424/423 – 348/347 B.C.) and his followers. They believed that the senses were invalid and that knowledge came by intuitively identifying natural forms in the mind from which further knowledge was deduced (Locke, 2007).

Deduction involves going from the general to the particular (Hyde, 2000; Riege, 2003). Thus, deductive thinking begins with having a tentative hypothesis, or a set of hypothesis in mind, which form a theory or generalisation (Hyde, 2000). Then, the researcher proceeds to observations to test the hypothesis, therefore the theory

(Bendassolli, 2013). As a result, the theory is either confirmed of rejected. Figure 4.2 illustrates the deductive thinking process.

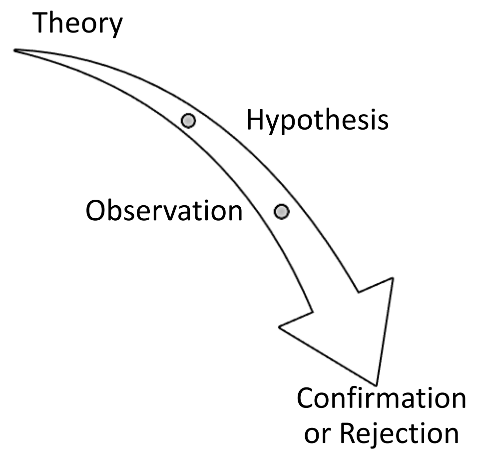


Figure 4.2 The deductive thinking process (adapted from Skinner, 2010)

Positivism is characterised by a deductive method of inquiry, which is seeking for theory confirmation in value-free statistical generalisations (Hyde, 2000). This way, it assures the researcher that there will be no deviation from the application of the theory in question (Levin-Rozalis, 2004).

4.3.2. Induction

Aristotle (384-322 B.C.) credits Socrates (470/469–399 B.C.) with the discovery of the method of induction: the process of proceeding from particulars to the general (universals) (Locke, 2007). Francis Bacon (1561-1626) championed induction, based on Aristotle's actual approach of using the senses to observe similarities and differences between existents (Locke, 2007).

In contrast to deduction, induction is about theory-building instead of theory-testing (Riege, 2003). Therefore, the Inductive approach to enquiry, follows the opposite rule to deduction, building generalisations out of observations of specific events (Skinner, 2010). Their primary interest is to achieve understanding of a particular situation, or individuals, or groups of individuals (Bendassolli, 2013). Thus, Inductive reasoning is seeking to establish generalisations from particular instances to a general law, rule, or pattern (Hyde, 2000). Figure 4.3 shows the inductive thinking process.

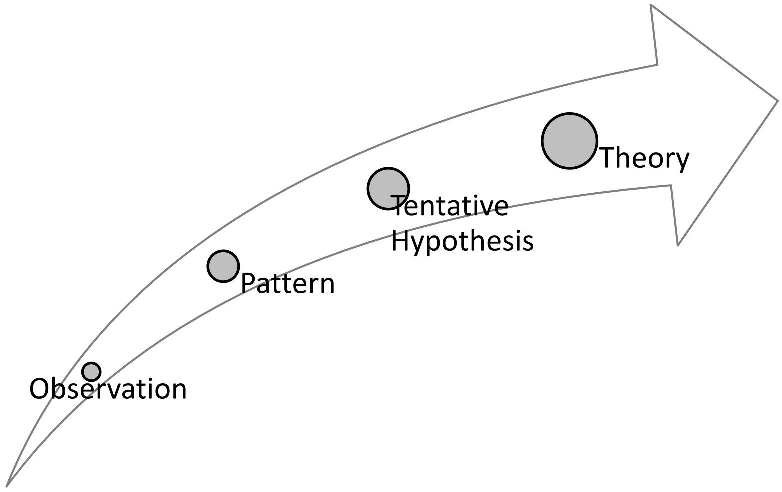


Figure 4.3 The inductive thinking process (adapted from Skinner, 2010)

Constructivism research utilises inductive methods that serve the purpose of discovering and building theory through analytical generalisations (Riege, 2003). Inductive thinking has been considered problematic because there is uncertainty regarding the fact that a recurring (known) event will continue to occur (Bendassolli, 2013). The problem of Induction, is also known as "*Hume's problem*", referring to the process of justifying knowledge (Buckle, 2004). According to Hume (1974), there are two primary ways to validate knowledge: by logic, as in the relation of ideas (for example, in mathematics), and by experience, in the case of matters of fact (Buckle, 2004). Knowing facts is thought to be equivalent to identifying their causes and effects (Bendassolli, 2013). It is believed that inductive research, in naturalistic settings - small samples, which permit repeated contacts with respondents and greater involvement of the investigator - enhance the validity and reliability of research (Crouch and McKenzie, 2006). Therefore, the basis for generalisation in qualitative study is analytical generalisation rather than statistical probability (Hyde, 2000; Riege, 2003; Yin, 2013).

Knowledge can be constructed on the basis of repeated observations, to the point where no observational statements conflict with the law or theory thereby derived, or up to an established saturation point (Bendassolli, 2013).

4.3.3. Abduction

It is considered that the concept of abduction was originally introduced by Aristotle, but it is the American philosopher Charles Sanders Peirce (1839-1914) who developed it into an explicit theory of inference (Svennevig, 2001). Peirce proposed that the traditional modes of inference (induction and deduction) should be complemented by a third mode (abduction), which is qualitatively different from the two others (Svennevig, 2001). Furthermore, it has been argued that the qualitative researcher can adopt both inductive and deductive processes (Hyde, 2000).

Abduction, also shares common aspects with grounded theory, as an iterative (abductive and deductive), evolving process based on observation and reflexion, which uses comparative analysis (Bendassolli, 2013; Ong, 2012). Thus, Abduction is a cyclical process of discovery and reflection that intends to provide explanations for new or surprising facts (Dubois and Gadde, 2002; Peirce, 1955). Systematic combining during Abduction stimulates knowledge development through iterative dialogue between data, and existing theories and propositions (Dubois and Gadde, 2002; Olsen, 2004). The initial framework of the research phenomenon is evolving simultaneously with empirical observation towards new knowledge creation. In this process, the data is collected simultaneously to theory-building, which implies a learning loop of back and forth direction between theory and empirical study (Dubois and Gadde, 2002). Initially, researchers begin with observational data, acquired by either experimental or natural designs, and make inferences by utilising an inductive reasoning process (Bendassolli, 2013). As a result, theories or general-universal statements are proposed. Secondly, via deduction, these theories are used to explain the phenomena investigated (Bendassolli, 2013).

Figure 4.4 depicts the iterative abductive research cycle according to Schutt (2011).

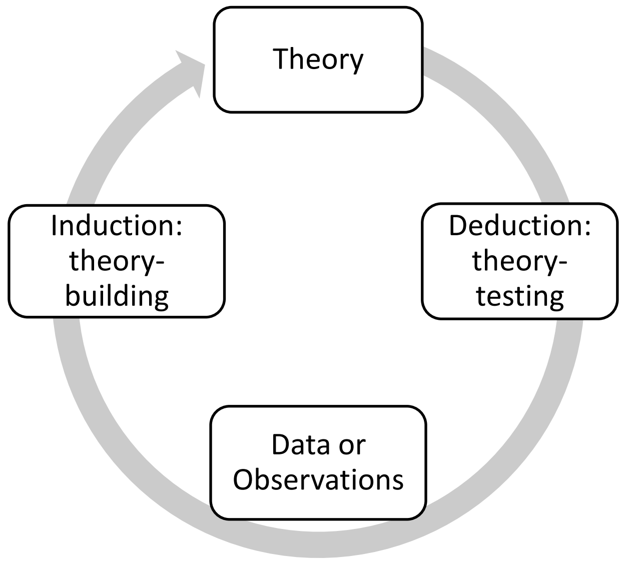


Figure 4.4 The abductive research cycle (adapted based on Schutt, 2011)

Abduction starts with consideration of facts, which are particular observations (Svennevig, 2001). These observations, then, give rise to a hypothesis that relates them to some other fact or rule, which accounts for them. This involves correlating and integrating the facts into a more general description, and relating them to a wider context (Levin-Rozalis, 2004). Thus, Abduction is the process of creating a novel type of combination between features present in data, as well as in theories (Kelle, 2007). Through theoretical triangulation, researchers deductively draw upon concepts from an extant theory in order to explain, accommodate, or embed their emergent theory (Reichertz, 2007). Depending on the creativity of the researcher, a *"mental leap"* is performed (Reichertz, 2007), through which previously un-associated things, become associated (Bendassolli, 2013). So, instead of reasoning deductively (from Rule, to Case, to Result) or inductively (from Case, to Result, to Rule), the abductive process is inferring a Case from a Rule and a Result (Svennevig, 2001), and then, iterates. Figure 4.5 shows the iterative abductive reasoning inference (from Rule, to Result, to Case, and then, back to Rule).

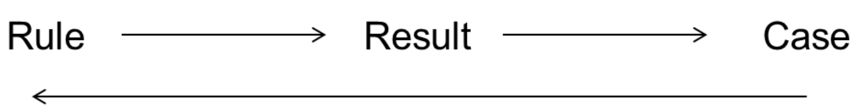


Figure 4.5 Abductive inference (from Rule, to Result, to Case, and then, back to Rule)

Relativism Realists or Pragmatists have been advocating the Abductive logic of analysis associated with the data creation process (Ma et al., 2008), since it has been claimed that *"Induction is unable to provide a solid basis for true statements"* (Olsen, 2004). Others claim that Abduction, like Induction, *"is also more or less probable, and not sure"* (Svennevig, 2001). Nevertheless, the goal is to understand verbal descriptions that are rich, rooted in locality, and phenomenologically accurate (Olsen, 2004). Additionally, Yin (2013) is advocating a deductive, rather than an inductive, approach to case study research (Hyde, 2000). Cases which confirm the propositions, enhance confidence in the validity of the concepts and their relationships, whereas cases which disconfirm the relationships, can provide an opportunity to refine the theory (Hyde, 2000). Thus, theory building and testing go hand in hand to establish valid theories, which are useful to managers as well as researchers (Meredith, 1993).

It has been argued that design synthesis is an abductive sense-making process as well (Kolko, 2010). Following the above principles, this research project is designed abductively, consisting of a series of inductive and deductive steps iteratively, while performing theoretical triangulation (e.g. general systems' theory) so as to develop a BIM-enabled SBD process. A conceptual framework has been initially developed utilising content analysis (see Section 4.7.1) and process mapping methods (discussed in Section 4.6) have been utilised to understand their relationships. The framework and models, have been iteratively tested and refined through a cyclical process. The research design of this project is explained in detail in Section 4.7 of this Chapter.

4.4. Research strategy

Naturalistic inquiry is characterized by research in natural settings (rather than in laboratories), qualitative methods, purposive sampling, inductive analysis, a grounded theory approach, a case study reporting mode, the tentative application of findings, and special criteria of trustworthiness (Lincoln and Guba, 1985). Qualitative research approaches can incorporate a variety of methods that seek to gain deeper insight and understanding. In this strategy, the research problem needs to be explored. It involves two types of data, exploratory and attitudinal (or predictive) (Naoum, 2007). Phenomenological research is considered both a philosophy and a strategy (Amaratunga et al., 2002). Ethnography is a strategy that a group is studied in its natural setting; observational and interview data are collected this way. Action research strategy differs from case study approach in terms that in the former method, the researcher provides solutions to the problem, while in the latter, the researcher observes without interfering (Naoum, 2007). Therefore, by implementing a case study approach for this study, the researcher has not interfered to alter the collaborative processes that occur during SBD implementation. It has been argued that case studies present the ideal setting for abductive research (Dubois and Gadde, 2002). As an example, Kohlbacher (2006) has described inductive and deductive cycles during content analysis of case studies. This Section discusses the research strategy implemented in this project, which is an abductive approach utilising multiple case studies to collect qualitative data.

4.4.1. Multiple case studies

In case study approach, the researcher explores in depth a situation with emphasis on understanding processes as they occur in their context (Amaratunga et al., 2002).

Case-oriented understanding has been defined as (Schutt, 2011):

> *"An understanding of social processes in a group, formal organization, community, or other collectivity that reflects accurately the standpoint of participants."*

According to Yin (2013) *"the distinctive need for case studies arises out of the desire to understand complex social phenomena"* because *"the case study method allows investigators to retain the holistic and meaningful characteristics of real-life events",* such as organizational and managerial processes (Kohlbacher, 2006). Case studies seem to be the preferred strategy in exploratory research when (Yin, 1981): (i) "*how*" or "*why*" questions are being posed; (ii) the investigator has little control over events; and (iii) the focus is on a contemporary phenomenon within some real-life context. This effort to "*understand*" what happened in these cases gives a much better sense of why things happened as they did (Schutt, 2011). Case study has demonstrated its appropriateness to generate a well-founded interpretive comprehension of human/technology interaction in the natural social setting (Andrade, 2009; Orlikowski and Baroudi, 1991). In addition, case study has affirmed its usefulness for theory-building that is strongly attached to empirical study (Andrade, 2009; Eisenhardt and Graebner, 2007; Eisenhardt, 1989). Furthermore, case studies have scope to be either Positivistic (quantitative) or Phenomenological (qualitative) (Amaratunga et al., 2002), and thus, everything in between (Pragmatic).

A holistic case study allows the researcher to understand one unique case. In contrast, a multiple case study design, examines several cases to understand the similarities and differences between the cases (Baxter and Jack, 2008). Yin (2013) describes how multiple case studies can be used to either: (i) predict similar results (a literal replication), or (ii) predict contrasting results but for predictable reasons (a theoretical replication). Although this type of research design has its advantages and disadvantages, overall, it is considered robust and reliable, but it can also be extremely time consuming and expensive to conduct (Baxter and Jack, 2008). Furthermore, a multiple case study design enables the researcher to identify how a phenomenon is influenced by its context (ibid.). Additionally, the case study research method is considered particularly well-suited to Information Systems (IS) research, when the interest has shifted to organizational rather than technical issues (Myers, 1997). What needs to be stressed at this point is that the method selected for this project is to be reflective without interfering with the cases (Drongelen, 2001):

> *"In the explorative multiple reflective case study the researcher does not actively participate in the regulative cycle but merely observes specific problem solving processes and collects "best practices" which are subsequently compared and analysed to extract the underlying principles."*

The limitation of the case study approach is that only a few number of studies can be conducted during the course of a project. In this study, the case studies investigated the individuals, groups, and organisational structure related to one subject study instead of the whole population of cases. The incidents' narratives related to the case studies attempted to understand the specifics of each case (see Section 4.7). The main strength of case study research lay in performing convergent, in-depth interviews, and their iterative nature (Yin, 1994). Another strength of this method is the synergic effect of a group setting (Riege, 2003). However, in this research, the group setting was not always possible to be realised for all cases due to lack of accessibility. As a result, most interviews were performed individually. During this research study, within four years, four sets of in-depth interviews were conducted, resulting in a total of 32 semi-structured interviews with industry experts from 17 organisations. Fourteen (14) "*best practice*" case studies were identified, and 20 incidents' narratives were collected to examine roles and responsibilities, resources, information exchanges, interdependencies, timing and sequence of events, and decision points (see Chapter 6). In total, they resulted in approximately 30 hours of recorded material. Reports and documents were also collected for data triangulation. Table 4.2 provides a summary of the case studies performed, and the design roles interviewed for each case.

Table 4.2 Case studies' summary and roles interviewed

No.	Building Project Type(s)	Certification(s)	Sustainability Objectives and Benchmarks	Design Roles Interviewed
CS1	Primary School	BREEAM Excellent, Passivhaus	BREEAM Excellent; 20% of energy use from renewable sources; Passivhaus certification; minimise embodied carbon of materials and systems; minimise energy use and the overheating of spaces; maximise daylight performance; maximise natural ventilation.	Architect, Passivhaus Consultant
CS2	Higher Education	BREEAM Outstanding, Passivhaus	BREEAM Outstanding; Passivhaus certification; specific attention to embodied carbon; minimize the embodied energy and embodied carbon of materials; minimise energy use and lifecycle carbon; maximise daylight maximise natural ventilation; maximise use of timber; test robustness for a 100 years.	Architect, Passivhaus Consultant
CS3	School	Passivhaus	Passivhaus certification; innovation; maximise the use of low impact materials (such as timber cladding); maximise daylight; maximise natural ventilation.	Architect, Sustainability Consultant, BIM Manager
CS4	Public Library	BREEAM Excellent	BREEAM Excellent certification; compliance with English Heritage; functionality; implementation of state of the art heating combined cooling/heating power system (CCHP); maximisation of daylighting; maximise natural ventilation; retaining the external and internal fabric of the existing building.	Architect
CS5	College	BREEAM Excellent	BREEAM Excellent; 10% renewable energy; 25% uplift on Part L; maximise natural ventilation; minimise embodied energy; selection of category A and B materials.	Architect, Sustainability Consultant
CS6	Hospital	BREEAM Excellent	BREEAM Excellent certification (9 point for energy performance); 40% uplift on Part L; efficient solar shading; maximise airtightness (2 air changes per hour); maximise insulation; minimise environmental impact.	Architect, Sustainability Consultant
CS7	Museum	BEAM Plus	BEAM Plus (a comprehensive environmental assessment scheme widely adopted in Hong Kong, similar to BREEAM and LEED); minimize energy consumption; reduce greenhouse gas emissions; Integrated Sustainable Building Design (ISBD).	BIM Coordinator

No.	Building Project Type(s)	Certification(s)	Sustainability Objectives and Benchmarks	Design Roles Interviewed
CS8	Office	BREEAM Excellent	BREEAM Excellent and A-rated Energy Performance Certificate (score 22); 96% of demolition and 94% of construction waste; renewable technologies for hot water, space heating and cooling.	BIM Manager, BIM Coordinator
CS9	Office	BREEAM Excellent	BREEAM Excellent; maximise daylight and natural ventilation, venting and cooling, passive heating, flexibility, disabled access, and new technology (Solartubes, thermal mass, solar control glass, low energy fitments, gas/biomass boilers, rainwater harvesting, local sensors).	Sustainability Director, BREEAM Assessor, Architect
CS10	Higher Education	BREEAM Excellent	BREEAM Excellent; daylighting and solar control; power source selection; heating and cooling strategies.	Architect
CS11	Non-domestic (unspecified)	BREEAM Outstanding	Zero emissions, zero carbon, low impact systems, timber frame, daylight, natural ventilation. BREEAM objectives: energy (mandated), monitoring, responsible sources materials, and management credits.	BREEAM Assessor, Sustainability Consultant
CS12	Shopping Centre (ongoing project)	BREEAM, Level 2 BIM maturity	BREEAM Excellent or Outstanding; optimise building geometry, thermal mass and embodied carbon of materials; estimate energy consumption; assess overheating and solar performance.	Architect
CS13	Office	BREEAM	Low energy and specific performance metrics, overshadowing, solar shading, optimisation of orientation to reduce the heating and cooling loads, natural ventilation, thermal mass, and daylight performance, air-tightness of fabric.	Sustainability Director, BREEAM Assessor
CS14	Office	BREEAM	Overshadowing and access to daylight, thermal performance and photovoltaics potential (solar analysis), HVAC performance, energy consumption, carbon emissions, heating and cooling loads, alternative and renewable technologies, fabric (U-Values, G-Values), shading devices, regulatory compliance (Part L).	Sustainability Engineer, BREEAM Assessor

4.4.2. The unit of analysis

The case study design is suitable for assisting the researcher in the definition of the unit of analysis to be studied, which is a *"bounded system … by time and place"* (Andrade, 2009; Creswell, 2012). Therefore, the unit of analysis of a case study is the major entity studied, that is related to the initial research questions (Yin, 2013). For each case, each project team, is considered as a single sub-unit of analysis under a holistic multiple-case study design (Downe-Wamboldt, 1992; Graneheim and Lundman, 2004; Yin, 2013).

The purpose of this project is to identify the critical components of a BIM-enabled SBD process, and explore their relationships so as to achieve environmental objectives in the most economical way possible in terms of time, cost, and effort (thus, sustainable). In-depth interviews, and narratives aimed to investigate the existing processes and workflows through successful and unsuccessful examples of SBD processes, based on the experts' interpretations. For this purpose, the methods and tools that facilitate SBD have been explored. Therefore, the unit of analysis of this research is the critical incident's narrative so as to understand the "*best practices*" for an efficient *"sustainable building design process".*

4.4.3. Sample selection - best practices

On one hand, the aim of quantitative sampling is to draw a representative sample from the population, so that the results of studying the sample can then be generalized back to the population (Marshall, 1996). On the other hand, the samples of qualitative studies are generally much smaller than those used in quantitative studies (Crouch and McKenzie, 2006; Mason, 2010). This fact relates to the aim of the qualitative approach, which is that the improved understanding of complex human issues is more important than generalizability of results (Crouch and McKenzie, 2006; Hyde, 2000; Riege, 2003; Yin, 2013). This explains why probabilistic sampling is neither productive nor efficient for qualitative studies, and why alternative strategies are used (Marshall, 1996). The iterative process of qualitative study design means that samples are usually theory-driven to a large extent (Marshall, 1996).

Therefore, for multiple case studies research, it is imperative that the cases are chosen carefully so that the researcher can predict similar results across cases, or predict contrasting results based on a theory (Yin, 2013). Furthermore, it is important to select the sample in a systematic way so as to ensure that it is credible and indicative (Malterud, 2001). What is important is to try to avoid biases by identifying roles and combining different perspectives into the research. Thus, purposeful sampling is implemented in qualitative research that seeks information-rich cases, which can be studied in depth, so as to learn a great deal about issues of central importance to the research (Coyne, 1997; Patton, 1990).

A non-probabilistic, purposive sampling approach was followed in this research, based on selection criteria for the best practices. The best practices are defined as those that are able to achieve high standards for environmental performance, and human comfort and health as well as business and commercial objectives such as BREEAM, EPC, and Part L rating so as to ensure a sustainable design outcome. Furthermore, the best practices manage to realise a quality outcome within the set project programme and budget by following sustainable project delivery methods that avoid unnecessary re-work and delays. For this reason, Expert Sampling has been used (Klein et al., 1989), that is, a selected sample of persons with known or demonstrable experience and expertise in the area of SBD. Hence, the "*best practices*" are defined as the ones that manage to achieve environmental objectives in the most economically efficient way in terms of time, cost, and effort involved. The interviewees were selected based on relevant educational background (in architecture, engineering, environmental physics, or sustainable design), varying industry experience (5 to 25 years), involvement in award-winning projects for sustainability (CIBSE Building Performance Award, UK Passivhaus Awards, RIBA Sustainability Award, BREEAM Outstanding or Excellent, and Sustainable Project of the Year), and for being part of organisations with BIM adoption policy (Level 2 maturity projects, and/or BRE BIM Certification).

Types of sampling implemented by this research during the four sets of data collection (Phases explained at Section 4.7):

- Phase 1 (Exploratory stage): Theoretical sampling (Bowen, 2008; Glaser, 1978) (while shaping the research hypothesis); theoretical frame although selective still not defined sufficiently to qualify for purposive sampling. Early decisions are based on general understanding of the researcher regarding the subject and problem area.
- Phase 2 (Main data collection stage): Criterion sampling (Coyne, 1997; Ritchie et al., 2013); serves to investigate in depth a particular type of case and identify all sources of variation.
- Phases 2 and 3 (Main data collection and Validation stages): Snowball or chain sampling; locate one or two key individuals, and then, ask them to name other informants that also meet the criteria, when possible. Serves to facilitate the identification of hard-to-find cases that are inaccessible (Baker and Edwards, 2012; Davies and Dodd, 2002; Ritchie et al., 2013).
- Phases 2 and 3 (Main data collection and Validation stages): Stratified sampling or purposive sampling (Barbour, 2001; Coyne, 1997; Patton, 1990); controlled by the researcher (Barbour, 2001). Serves to illustrate characteristics of particular subgroups of interest and facilitate comparisons.

Targeted extensive research was undertaken to identify suitable industry experts, following a Pragmatic approach. This way, the researcher was not limited to implementing a single method, but explored the advantages of each of them, and chose depending on the circumstances. Theoretical sampling was considered the most appropriate method at the early stages of the research (Exploratory, Phase 1), when the understanding of the problem was still shaping. Then, during Phase 2, Criterion sampling served to investigate particular cases (best practices). During this time, the Snowballing technique was useful to reach SBD experts, nominated by their colleagues. Finally, Stratified sampling was implemented in cases when the researcher aimed to complete gaps in the process model in order to reach theoretical saturation. Furthermore, a controlled group of participants was selected, during

Validation stage (Phase 3) of the research, so as to gather the varying perspectives of stakeholders. As a result, a representative group of different SBD specialisations and expertise was selected. Also, both previous and new participants to the study were selected to ensure the internal as well external validity of the research outcomes. The protocol for recruiting participants is discussed in Section 4.4.5 of this Chapter.

4.4.4. Sample size – theoretical saturation

Sample size has a significant effect in the quality of qualitative research (Coyne, 1997). The number of required subjects usually becomes obvious as the study progresses, as new categories, themes, or explanations stop emerging from the data (data saturation) (Marshall, 1996; Mason, 2010). This strategy requires a flexible research design and an iterative, cyclical approach to sampling, data collection, analysis, and interpretation (Marshall, 1996). Thus, by utilising an abductive research approach, it was possible to determine the appropriate sample size for this study.

Determining and proving theoretical saturation is challenging (Morse, 1995), since it is considered an *"elastic notion"* (Mason, 2010). In theory, new data may always emerge, but the returns after a certain point are diminishing, not adding anything significant to the study in relation to the research questions. Therefore, a sample is considered adequate when depth as well as breadth of information has been achieved (O'Reilly and Parker, 2012). Several researchers have explored the number of participants that are adequate for a qualitative sample (Guest et al., 2006). For example, Charmaz (2006) suggests 25, Green and Thorogood (2013) recommend *"20 or so people",* Creswell (2012) advices for 5 to 25 for a phenomenological study and 20 to 30 for grounded theory study. Mason (2010) has performed a variety of statistical tests (between 560 studies), and the most common sample sizes have been found to be 20 and 30. Moreover, Baker and Edwards (2012) have gathered a set of 14 *"prominent qualitative methodologists*" to rationalise the issue of sampling size. Their positions range across epistemological and disciplinary stances, and academic styles. The main arguments presented are the following:

- The breadth and scope of research questions vary quite a lot in qualitative research and this too is likely to influence sample size (Alan Bryman, University of Leicester).
- A standard answer to the question of how many interviews is that it depends on your research purpose (Kathy Charmaz, Sonoma State University).
- It is better to aim to offer sound qualitative insights, than try to mimic a quantitative "*representative*" logic (Jennifer Mason, University of Manchester).
- In practice, apart from when researching their PhD, few professional anthropologists gain more than very occasional opportunity, money and time to carry out this kind of full ethnography. So clearly we need to be pragmatic and recognise that often circumstances dictate a reliance upon interview data (Daniel Miller, University College London).
- Essentially, *"You should stop adding cases when you are no longer learning anything new."* (Charles C. Ragin, University of Arizona).

It is apparent that sampling size depends on the purpose of the research and the notion of an adequate sample for qualitative research cannot be quantified explicitly. For this research, four sets of data collection with in-depth interviews, were performed. These have resulted in a total of 32 semi-structured interviews with industry experts from 17 organisations that implement SBD. By implementing an abductive approach, qualitative data analysis occurred concurrently, and in-between sets of data collection, so that the researcher could generate an emerging understanding about the research questions, which informed both the sampling and the questions being asked moving forward. This iterative process of data collection and analysis led to a point, in the data collection, where no new categories or themes emerged. This is the point of theoretical saturation, or information redundancy, signalling that data collection is complete (DiCicco-Bloom and Crabtree, 2006).

4.4.5. Recruiting participants

Describing sampling strategies in detail and with transparency affects replication of the study (Coyne, 1997). The first step of recruiting participants for the study was identifying them, based on the set of criteria discussed in Section 4.4.3. Then, once their credentials were assured, and their contact details obtained through background research, an initial e-mail was sent to them personally (found in Appendix B). This first correspondence is considered crucial, thus a recommended protocol was implemented to increase the rate of responses (Rowley, 2012):

i. Indication of who the researcher is (including the university and course), and purpose for conducting this research.
ii. To capture the interest of the potential interviewee, a brief explanation of the research was provided.
iii. A clear account, as to the amount of their time that the interview required, was provided.
iv. Permission to record the interview was asked, once they accepted the request.
v. Assurance of confidentiality at all times was stated.
vi. Details regarding benefits to them were discussed during correspondence.
vii. Contact details of the researcher (email and phone number) were provided in advance, as well as indicative availability (two weeks).
viii. Follow-up e-mails were sent, when the initial contact did not provoke a response (after one week).

Once the participants accepted the request, a date and time was suggested by the researcher, in cases that the participants did not state an available date (as indicated in the recruiting e-mail). The challenges that this procedure encountered were that the people that successfully utilise BIM for sustainable design, in the UK, are not easily accessible, and also hesitant to reveal confidential project information and empirical experience that are considered to give them competitive edge as early adopters. Based on the Pragmatic approach, an important factor that has determined the sampling size was the number of willing participants that could be identified as wells as the length of time that they were available to spend for the interviews (Rowley, 2012). Table 4.3 summarises the recruitment statistics (number of experts contacted and responses) indicating both positive [+] and negative [-] outcomes.

Table 4.3 Number and percentages of identified experts and their responses – positive [+] and negative [-] outcomes are indicated

Type of participant response	*Number*	*Percentage*
Email failed to be delivered [-]	26	6.9%
Automatic response - absent [-]	18	4.8%
Respondent refused invitation/nominated colleagues [-]	16/14	4.2%/3.7%
Initially accepted but then dropped out [-]	10	2.6%
Non responses [-]	276	73.0%
Nominated by colleagues and performed interview [+]	4	1.1%
Responded to original email and performed interview [+]	28	7.4%
Contacted [total]	378	100%

4.5. Research methods

Methods are the specific techniques and procedures used to collect and analyse data (Crotty, 1998). According to Creswell (2009), there are three types of research designs: qualitative, quantitative, and mixed methods. This Section discusses the above mentioned methods and presents the ones selected in this research. The research design is synthesised chronologically in Section 4.7 of this Chapter.

4.5.1. Quantitative

The quantitative research approach stems from the Positivist philosophy; it starts with a hypothesis or a general statement evolving from the literature and proposes a general relationship between variables (Creswell, 2009). Usually this approach is based on measuring and counting, and involves collecting and analysing numerical data and applying statistical tests. As a result, an Objective position is necessary for interpreting the results. For example, a survey is a quantitative method utilised in social research, which provides numeric data by asking precise, narrow questions (Fellows and Liu, 2009).

This research implemented a quantitative approach, during validation, where structured questionnaires were distributed to the focus group. Those included survey responses (selecting options by ticking the appropriate boxes), attitudinal responses, and five-level Likert scale (Strongly Agree to Strongly Disagree) (see Appendix B). This method facilitated the validation of the developed research framework in a transparent way. A five point rating scale was selected, which included a neutral step for neutral attitudes. The questionnaire was tested in two pilot workshops with 8 participants, experts in SBD. The pilot tests assisted in determining flaws and limitations of the design, and provided feedback that allowed revisions before the implementation of the study (Kvale, 1994; Turner, 2010). The results of the validation workshops and interviews are presented in Chapter 7.

4.5.2. Qualitative

Qualitative research follows the Constructivist philosophy, and is usually adopted to explore and understand the meaning individuals or groups attribute to a social or human problem (Creswell 2009). Qualitative research seeks to find answers such as why things happen, through Interpretivism, which means defining the meanings which people attribute to events and processes (data derived from peoples' perceptions) (Fellows and Liu, 2009). Qualitative methods aim to discover new relationships of realities and built up understanding of the meanings and experiences (inductively), rather than verify a predetermined hypothesis (deductively) (Riege, 2003). Strauss and Corbin (1990) have claimed that qualitative methods can be used to better understand a phenomenon about which little is yet known. Despite the known benefits of qualitative research, its main disadvantage is that it is very time consuming (Hoepfl, 1997). Qualitative methods are appropriate in situations where the researcher needs to first identify the variables that might later be tested quantitatively (ibid.). Furthermore, qualitative interviews are considered an appropriate strategy for Information Systems' (IS) research (Silverman, 1998).

This study implemented a number of qualitative methods, which included a thorough literature review (presented in Chapters 2 and 3), exploratory interviews (with 5 participants), in-depth case study interviews (with 20 participants), and two validation workshops (with 8 participants) as well as in-depth validation interviews (with 7 participants). The amount of time and resources available is a critical factor in qualitative research that should not be underestimated (King, 1994; Marshall, 1996). The time spent to recruit participants, carry out interviews, travel to and from them, transcribe, analyse transcripts, and feedback findings was significant. Details regarding the interviews' protocol are described in Section 4.7.

4.5.3. Mixed methods

Mixed methods combine both quantitative and qualitative forms and, by implementing this design, the researcher integrates what is learned from one method into another method (Axinn and Pearce, 2006). Adoption of this approach means that the researcher collects different kinds of data, and thus, the study is strengthened (Creswell and Clark, 2007). Therefore, an eclectic rather than restrictive approach is implemented so as to obtain useful answers (Johnson and Onwuegbuzie, 2004). Mixed methods indicate that the study consists of both deductive and inductive approaches (Dainty, 2008). It is also argued that dichotomous, un-dimensional distinction between quantitative and qualitative approaches is not particularly useful because it ultimately refers only to whether the data is into number or text and is considered to be far too simplistic (Axinn and Pearce, 2006).

Figure 4.6 illustrates the framework of research designs according to Creswell (2009). The selection of research strategy and methods happens in accordance with the philosophical worldviews of the researcher. This research follows the Pragmatic paradigm throughout the research design, data collection, and analysis. A number of qualitative methods were adopted, which include a thorough literature review, exploratory interviews, in-depth case study interviews, and validation interviews. Although the study mainly utilises qualitative methods, it is also complemented by mixed methods of data collection such as documents relating to the case studies, structured diagramming techniques to map SBD processes (see Section 4.6), and structured questionnaires during validation (found in Appendix B).

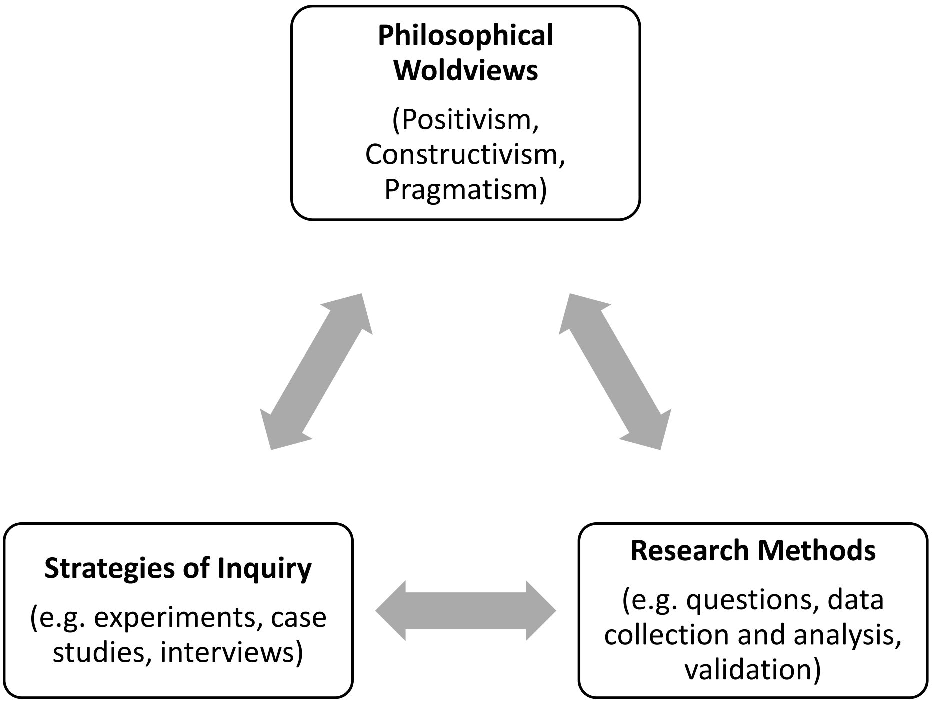


Figure 4.6 Framework of research design (adapted from Creswell, 2009)

Yin (2013) has discussed six sources of evidence from case study research: (i) documentation, (ii) archival records, (iii) interviews, (iv) direct observations, (v) participant observation, and (vi) physical artefacts. To address the lack of measurability in interview research, which is based on the interpretations of the researcher, triangulation of the data was implemented whenever possible (Johnson and Onwuegbuzie, 2004). The triangulation method is considered to be a very powerful one as it combines the strengths and offsets the weaknesses of both qualitative and quantitative methods (Bryman, 2006; Creswell, 2009), increasing the validity and reliability of the data (Amaratunga et al., 2002). According to Yin (2013), *"data triangulation … essentially provide[s] multiple measures of the same phenomenon".* Interpretive researchers prefer the term corroboration defined as *"the act of strengthening [an argument] by additional evidence"* (Andrade, 2009). This research implemented a qualitative approach to theory development while triangulating (corroborating) and complementing the findings by collecting documents related to the case studies (Bryman, 2006). Additionally, the theory was tested quantitatively, during validation, utilising structured survey questionnaires while triangulating qualitatively with in-depth critical questions that provided justifications to the responses. Corroboration of methods, during this study, provided assurance towards the validity and reliability of the responses and assisted in identifying conflicting responses of individuals. When that was the case, the researcher attempted follow-up questions to clarify the intent of the responding party and resolve possible misunderstandings.

4.6. Conceptual process modelling

A model is a *"simplified representation or abstraction of reality"* (Meredith, 1993). The primary difficulty in using models to analyse situations is obtaining adequate simplification, while maintaining sufficient realism (ibid.). An organisational diagram (used in this study) is considered to have a mid-level of abstraction to the original system, which means that while it does not look like the system (as physical models do), it behaves like the original system without being symbolic (e.g. mathematic equations). A conceptual model, in this study, is defined as a set of constructs, inferred by observable events, used to describe an event, object, or process (Meredith, 1993). Thus, the identified propositions in a conceptual model are logical rather than epistemological.

Although General Systems Theory (GST) (Von Bertalanffy, 1969) - discussed in Chapter 2 (Section 2.3.3.3) - has its roots in biological science, it has been utilised effectively to address organisational problems (Walker, 2007). Thus, human beings and business organisations can be analysed as open systems (Jennings and Wattam, 1998). Each requires inputs from the environment in order to continue their functioning. The inputs are transformed to become outputs back to the environment. The systems approach provides a distinctive, holistic view of a situation, and the problems that are associated with a situation. Organisations are divided into sub-groups by functions and by hierarchy. By describing and analysing situations as systems, an integrated view is developed where the effects of the various subsystems on each other can be identified. Therefore, for a system to perform at its best, then all the conceptual entities of the system need to perform at their best. In addition, the interdependencies of entities (the timing, and sequencing of events) are critical to achieve environmental goals during SBD implementation. One of the first approaches to systems modelling happened by the Tavistock Institute of Human Relations, at the request of Building Industry Communications Research Project (1996) (cited in Walker, 2007). That review produced a report of communications in the UK building industry, which has used Operational Research to *"find out how the system works, the functions of different parts, their interrelationships with each other, the main centres of control and co-ordination, and what information is necessary in order that this control is exercised".* Following the same logic, this research has intended to define the entities of SBD (utilising content analysis), and the chain of interactions and choices among them, retrospectively from narratives, implementing the CDM (Klein et al., 1989), along with process mapping methods. It has been acknowledged that if everybody involved in a building project can work to an agreed set of processes and procedures, then, they are both more efficient and more likely to meet the client's needs (Kagioglou et al. 1999).

Chapter 2 has discussed the underpinning theories of this research, including GST (Von Bertalanffy, 1969) (open and closed systems), design theory, communication theory, and the concept of CE. Furthermore, the distinction between prescriptive (closed systems) and descriptive models (open systems) has been made clear (in Chapter 2). As discussed in Section 4.4, in case study research, the researcher observes without interfering (Naoum, 2007). So, although the SBD system is considered to be open, this method differs from Soft System Methodology (SSM) because the latter is used to implement an intervention to the system, and reconstruct it (Aguilar-Saven, 2004). For this purpose, it is more suited to action research rather than case study approach. The models developed in this study do not re-engineer the process, but rather adopt the suggestions of the best practices. Based on these principles, descriptive process models were developed, utilising the Integrated DEFinition (IDEF) family of methods (IDEF0 and IDEF3) for CE (Mayer, 1992), in order to map SBD processes of the best practices, and the Object Management Group's Unified Modelling Language (OMG UML) (OMG, 2011) to conceptualise process automation. The following sub-Sections discuss process modelling methods in detail, and the rational for selecting these techniques.

However, a conceptual process model does not provide a causal explanation of the system's behaviour, but a functional one. Therefore, it is not an actor-explanation but a process-explanation of observable features (Kuipers, 1986; Svennevig, 2001). Although the developed model motivates the rules and requirements of the activity, it does not relate to the actors intentions and motivations. To complement for this shortcoming in the interpretation of findings, thematic analysis was performed to synthesise the justifications, as provided by the participants, during the in-depth interviews. This analysis was necessary to better understand the rational between success and failure to efficiently achieve sustainability objectives. The research design and procedures for data generation and analysis are discussed in Section 4.7 of this Chapter.

4.6.1. Structured diagramming techniques

Martin and McClure (1985, cited in Hassan, 1996) identify the use of structure diagrams in four areas: (i) overview systems analysis: overall model of an organisation is drawn, processes are decomposed hierarchically and overall flow of data and processes are modelled; (ii) program architecture: is a set of programs showing separate modules of system architecture; (iii) program detail: detail logic within program module is designed, and (iv) data structure: database models and file representation are drawn. Based on the above descriptions, the IDEF0 and IDEF3 models developed in this research belong to the first category of "*overview systems* *analysis*", and are considered appropriate for examining the organisational processes of a system.

Structure diagramming techniques utilise both qualitative and quantitative methods (Forbus, 1984). Pryke (2012) has defined three approaches to modelling analysis: (i) tasks' dependency (e.g. critical path analysis), (ii) structural analysis (e.g. hierarchical management structures), and (iii) process mapping (e.g. cognitive mapping). One example of the first category is the Critical Path Analysis (CPA) utilising PERT (Programme Evaluation Review Technique) networks breaking down the project into a list of activities that need to be performed to complete the project. However, in CPA, the iterations required to reach a final, workable design are ignored (ibid.). The second category could be represented by the contractual tree, as presented by RIBA (2013) to describe authoritarian relationships within organisations. The third category includes cognitive mapping approaches that are highly specific and not useful for organisational processes. Pryke (2012), contrarily, has supported the use of Social Network Analysis (SNA) for construction management to address the issue of formal and informal management and communication between stakeholders. However, SNA focuses on the "*who*" or "*what*", while gives no indication regarding the "*how*". Therefore, it is assuming that the entities of the system perform effectively and it is concerned solely in their interactions. The above three categories of process mapping are representatives of absolute examples. The IDEF methods (IDEF0 and IDEF3) cannot be categorised explicitly to any of the above due to fact that they combine aspects of all of them, creating powerful descriptions, while remaining simple to understand.

Many authors have discussed the benefits and limitations of several structured diagramming techniques (Aguilar-Saven, 2004; Cooper, 2005; Dorador and Young, 2000; Eppinger and Browning, 2012; Hassan, 1996; Kagioglou et al., 1999; Pryke, 2012; Steele, 2000; Walker, 2007). A summary and critique of the reviewed methods is presented in Table 4.4. The IDEF methods were selected due to their high descriptive power, which is considered appropriate for detailed processes that handle know-how knowledge.

Table 4.4 Review of structured diagramming techniques

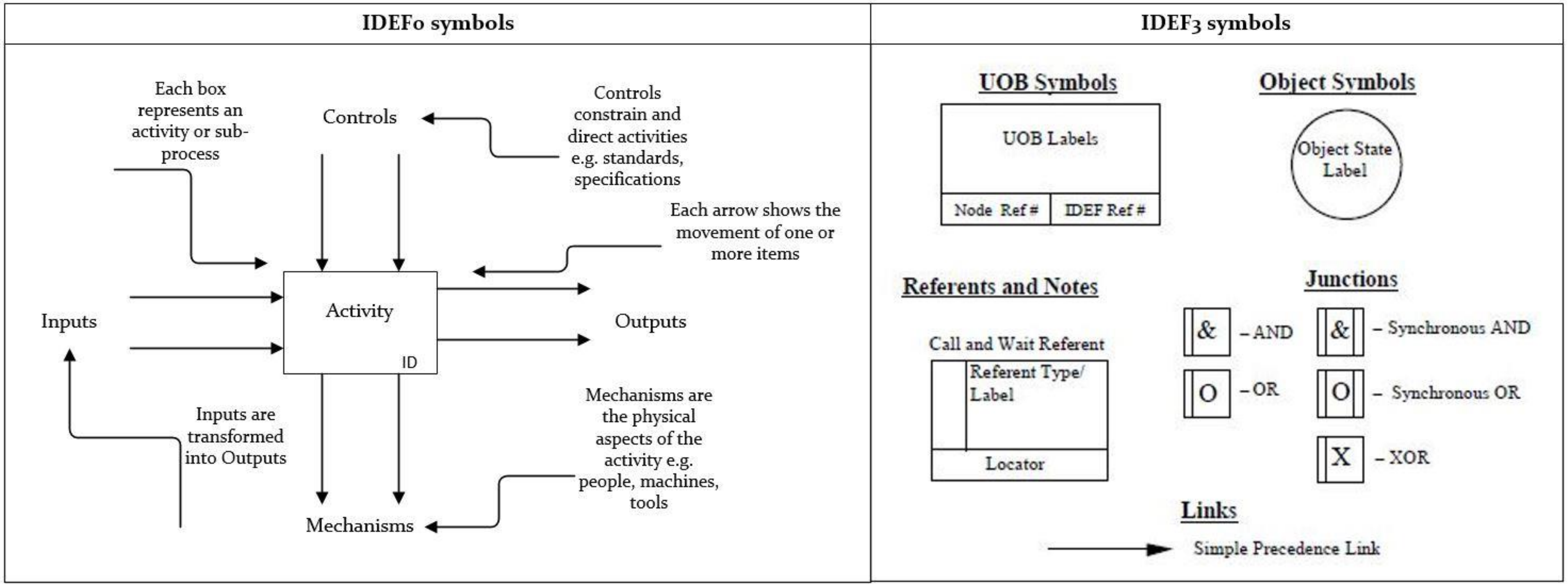
Technique	*Features*	*Strengths*	*Weakness*
Flowchart	Logical sequencing of actions, decisions, and attached information	Simple, flexible	No sub-layers, no specific method for implementation available
Gantt chart	Matrix representation of flow of activities in relation to time	Easy overview, simple	Dependencies not indicated sufficiently, no input/outputs
Petri Nets (PN)	System network, that comprises of transitions, places, tokens, and arcs	Well defined syntax, flexible, non-deterministic algorithm	Time consuming to create, no information transfer mechanisms, no hierarchy
Higher Order Software (HOS) chart	Functional decomposition, based on binary tree structures	Mathematically based tool, good for professional systems analyst (data flow modelling)	Complex, not user-friendly, prescriptive
Data Flow Diagram (DFD)	Data flow, that includes activities, information store, and source (or sink)	Top-down analysis, hierarchical, descriptive	No task dependencies, no iterative loops, no mechanisms
Hierarchical Input, Process Output (HIPO)	Set of diagrams that show input boxes, output boxes, and functions	Show flow of data, more suitable for small-scale systems	Shows "*what*" but not "*how*", difficult to draw

Technique	Features	Strengths	Weakness
Business Process Modelling Notation (BPMN)	Flow of events, activities, and gateways	Includes pools and lanes for participants, and artefacts (data object, group, annotation)	No hierarchical representation, no clear dependency between process models
Social Network Analysis (SNA)	Social structures modelled as a network utilising graph theory	Links between actors and information exchanges	No hierarchy, no tasks' representation, no activity flow
Program Evaluation and Review Technique (PERT)	Nodes represent events and arrows indicate the sequence of tasks (critical path)	Explicitly defines and makes visible dependencies, parallel or concurrent tasks considered	No resources, no completion time, no decision making points, sequential without iterations
Entity Relationship Diagram (ERD)	Description of objects as entities within a system and their relationships	Internal consistency, easy to create software, identify objects	Complex model, no process or information flow, static
Role interaction diagram (OMG UML)	Flows of activities and roles' interactions, sequential system behaviour	Intuitive to understand, clear notation principles	Not comprehensive, no inputs/outputs
IDEF0	Flow of activities, inputs, outputs, controls, and mechanisms - Structured Analysis and Design Technique (SADT)	Clear representation, good amount of information, permits iterative loops	Sequential waterfall diagrams, no clear distinction between roles and tools, no parallel activities
IDEF3	Flow of activities, objects, and decisions (process flow view and object state transition view)	Dynamic and comprehensive, flexible, allows parallel activities and iterations, includes multiple decision scenarios	Many sub-diagrams, a lot of data needed to be constructed, time consuming and complex to create

4.6.2. Integrated DEFinition (IDEF) methods (IDEF0 and IDEF3)

The IDEF0 is used to produce a "*function model*", a structured representation of the functions, activities, or processes within the modelled system or subject area (Lee and Barrett, 2003; Chin et al., 2006; Draft Federal Information Processing Standards, 1993). The IDEF (Integrated DEFinition language) family (Mayer, 1992; Mayer et al., 1994) has been adopted to map the sequencing and structure of the collaboration workflows (see Chapter 6, Sections 6.2 and 6.3). IDEF0 is widely used in research due to its clarity of modelling activities and information flows between them, as products of those activities. However, IDEF0 cannot support information process flows or capture concurrent processes and there is no consideration of time (Mayer and DeWitte, 1999). IDEF3 overcomes the shortcomings of IDEF0 by capturing descriptions about sequences of activities, while also identifying critical decision points, or milestones, of the process from different perspectives (Mayer et al., 1995). IDEF3 has specifically been developed to model stories (situation or process) as an ordered sequenced of events and activities (Mayer, 1992). It is a scenario-driven process flow modelling method created to map descriptive activities. The goal of IDEF3 is to provide a structured method for expressing the domain expert's knowledge about how a particular system, or organisation, works (ibid.). For these reasons, the IDEF3 Process Description Capture Method manages to remain simple while maintaining a high descriptive power (Dorador and Young, 2000). Table 4.5 shows the symbols used for the process description schematics. The IDEF0 method uses the ICOM (Input, Control, Output, and Mechanism) (KBSI, 1993). In IDEF3, the boxes represent real world processes as happenings; these are referred to as Units Of Behaviour (UOB). The arrows that connect the boxes indicate precedence between actions. The junctions represent constraints and enable process branching. Also, the junctions involve choices among multiple parallel or alternative sub-processes. The logical decisions include: AND (&), OR (O), and EXCLUSIVE-OR (X), and synchronous or asynchronous start and finish of the processes. The objects are illustrated as circles that represent their different states connected with arrows that have UOB's referents to indicate the entry, transition, state, and exit conditions (Mayer et al., 1995).

Table 4.5 Symbols used for process description schematics (Knowledge Based Systems Inc. (KBSI), 1993; Mayer et al., 1995)



4.6.3. Unified Modelling Language (UML) sequence diagrams

In Chapter 6 (Section 6.4), the behaviour of the proposed automated system is demonstrated utilising Use Case Scenarios. A Use Case is defined as *"a concrete description of activity that the user engages in when performing a specific task, description sufficiently detailed so that design implications can be inferred and reasoned about"* (Carroll, 1995). These Scenarios are based on the narratives that have synthesised the Level 2 sub-process decompositions of the IDEF3 model. UML sequence diagrams were developed to establish the interactions (Requests and Responses amongst the System and its Users) between the three layers of the system's architecture to show the interplay among the users, and automated functions (Satzinger et al., 2010). The OMG UML (Object Management Group's Unified Modelling Language) (OMG, 2011) notation was selected for this purpose due to its popularity and ease of use. The focus of a Sequence Diagram is the messages between the System's lifelines. Data may also be included although this is not the focus. The diagrams developed represent the layers of the system (i.e. Presentation, Service, Data and Knowledge Access) as Objects (rectangles) in vertical coordinate dashed lines (lifelines). When a target sends a message to another target, it is shown as an arrow between their lifelines. The arrow originates at the Sender and ends at the Receiver. A closed arrow filled arrowhead show that the message is sent synchronously. This means that the Caller waits until the Receiver has finished processing the message. When the Receiver returns control to the Sender, a dashed arrow is drawn. With asynchronous messages, the Sender does not wait for the Receiver to finish processing the message, and continues immediately. In that case, both Sender and Receiver are working simultaneously. As a result, a new thread (multithread) may start to demonstrate concurrent processes. An open arrowhead indicates that a message is send asynchronously. If a message includes a guard (condition to be met), then, it is shown between brackets. If multiple messages are sent in the same iteration, then, a loop fragment is used. The combined fragment is shown as an upward arrow with a "*loop*" operator plus a guard, which contains the conditional messages under that guard. Figure 4.7 illustrates the OMG UML Sequence Diagrams' notation (OMG, 2011).

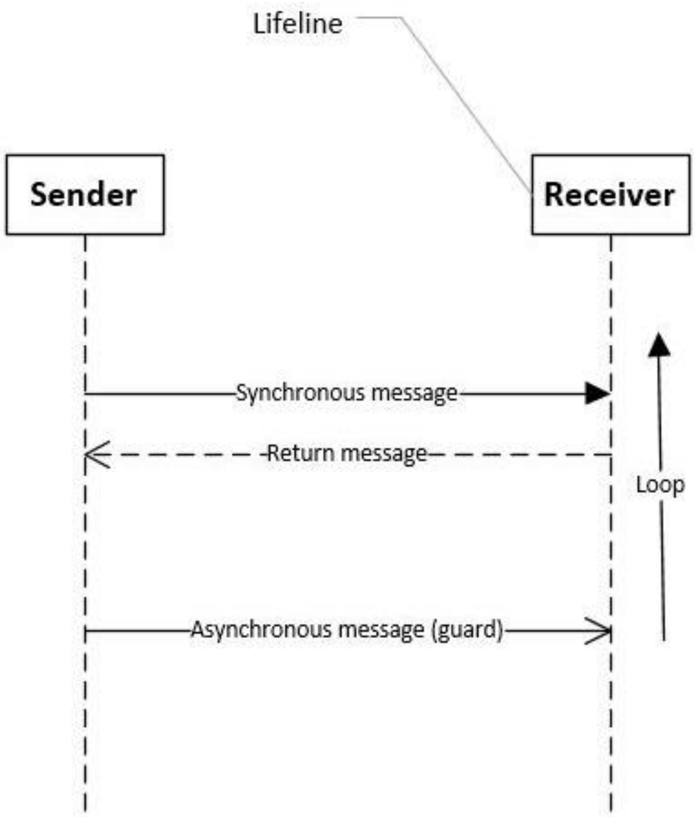


Figure 4.7 UML Sequence Diagram notation (adapted from OMG, 2011)

4.7. Research design and techniques

This Section provides a chronological account of decisions that took place during the research process, and describes data generation and analysis procedures in detail. This research has adopted an abductive approach using multiple case studies and semi-structured interviews (King, 1994). Content analysis (Elo and Kyngäs, 2008) was utilised to identify the components of SBD and develop the framework presented in Chapter 5. CE process modelling techniques (IDEF0 and IDEF3) were used to map the interdependencies of components, based on the narratives of the design teams' members (see Chapter 6, Section 6.3). A combination of qualitative methods were implemented for the analysis of the data (Schutt, 2011).

The *"iterative theory building process"* (Drongelen, 2001) was separated into three distinct phases that served as hard-gates during the research process, as illustrated in Figure 4.8. During the initial stage of data collection and analysis (Phase 1), an IDEF0 process model (KBSI, 1993) was created following the RIBA Plan of Work 2013 framework. The IDEF0 model was presented to the industry practitioners, and validated for its accuracy. In the following stage of data collection and analysis (Phase 2), IDEF3 process model decompositions (Mayer et al., 1995) were developed, based on the incidents' narratives. Here, 20 incidents' narratives were collected, and flowcharts of the collaboration workflows were developed. The experts were asked to identify examples of successful and unsuccessful collaboration workflows, based on the sustainability outcome. Based on the workflow patterns of successful examples, the complete IDEF3 process model decompositions were developed (exploratory identification of variables, properties, and relationships), consisted of four level hierarchies (high to detail). During the last interviews of this phase, the interviews' protocol and prompts were used to validate and refine the IDEF3 process model's decompositions. This process continued until no more information, related to the research questions, was provided by the experts (theoretical saturation/information redundancy) (Glaser and Strauss, 2009). During Phase 3, the components of the theoretical framework and process models' interdependencies were finalised, and then, a three layered system architecture was conceptualised as a recommendation. Two workshops with eight (8) academic participants were performed to validate the research framework and developed concept. Furthermore, seven (7) in-depth interviews were performed with industry practitioners. During the interviews, the IDEF model was presented, and validated for its accuracy and adequacy. The feedback received along with the amended IDEF model are presented and discussed in detail in Chapter 7 (Section 7.4).

The following sub-Sections describe the techniques adopted for collecting, analysing, and interpreting data throughout the research process. Furthermore, Section 4.7.4 discusses the quality criteria and controls that were considered to ensure the validity and reliability of the research outcomes.

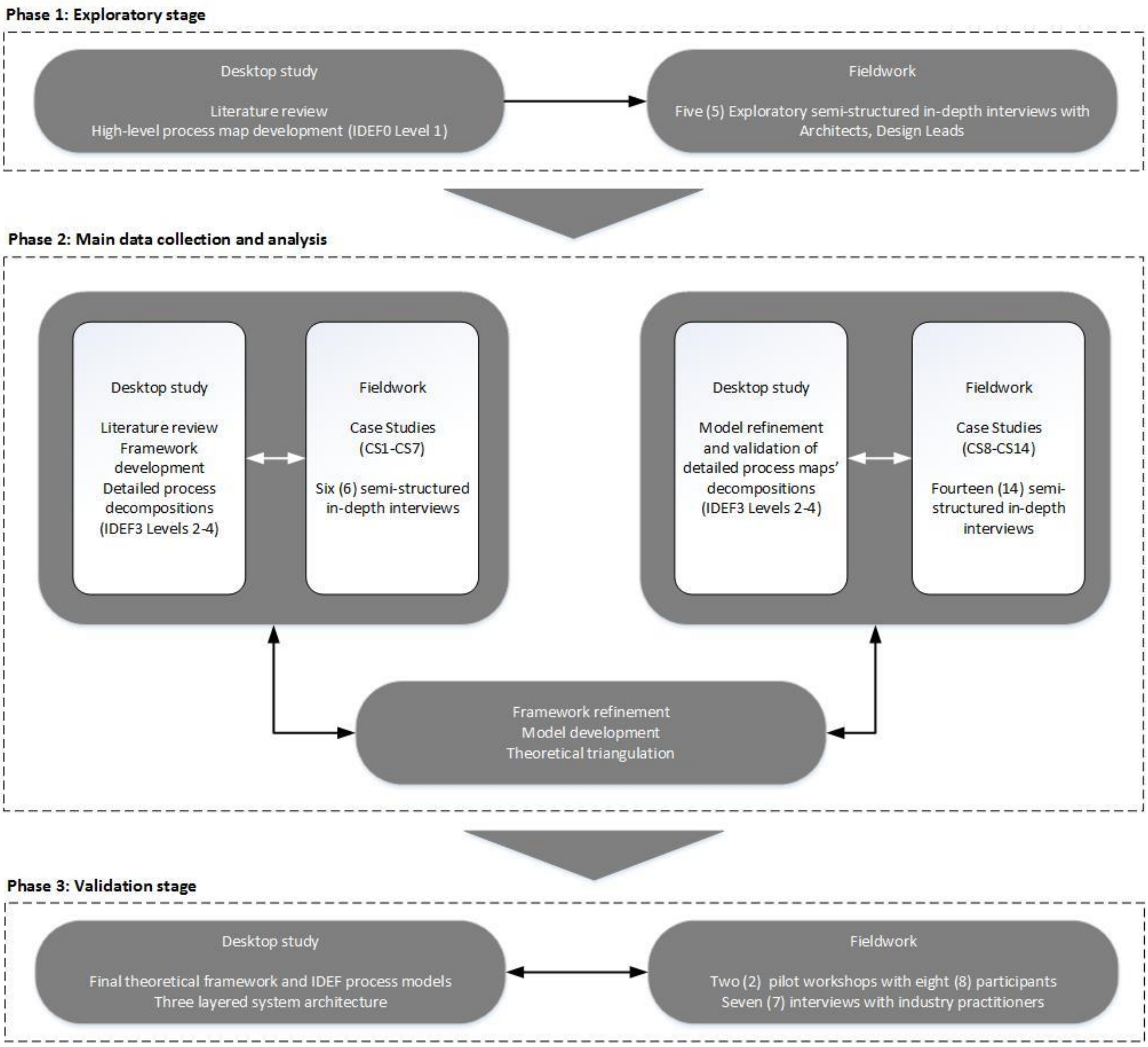


Figure 4.8 Overview of the research design (Phases 1-3)

4.7.1. Phase 1: Exploratory stage

The first stage of the research was exploratory, conducted to investigate the current stage of sustainability integration with BIM processes. This phase enabled to explore the feasibility of BIM-enabled SBD, and clarified the understanding of the researcher regarding the problem areas (Saunders and Lewis, 2000). Thus, the first step of the study was the preliminary research; this is considered an essential step in the design of an effective data collection procedure because it assists in anticipating constraints before launching the main body of data collection effort (Axinn and Pearce, 2006). The second step was to gain the foundation information that were necessary to select the research design parameters and information to determine the research design (Axinn and Pearce, 2006). The methods implemented at this stage consisted of an extensive literature review study, and in-depth interviews with experts in the field. The goal of the interviews was to collect "*facts*", as well as gain insights and understanding of experiences, processes, and predictions (Crouch and McKenzie, 2006; Rowley, 2012; Amaratunga et al., 2002).

So as to get a better understanding of the research problem, the collection of qualitative and quantitative data was both simultaneous and sequential. The research started as exploratory; the scope was to observe patterns, and identify the current perceptions and state of adoption of BIM and SBD as well as collaboration and communication methods. This has served to gain a better appreciation of the problem, identify research gaps, and develop research questions.

4.7.1.1. Phase 1-A: Literature review and content analysis

The first step of the research process was an inductive one. The literature review, presented in Chapters 2 and 3, has allowed the researcher to gain a deeper understanding regarding the concept of SBD and its management as well as the state of the art methods for its implementation utilising emerging technologies and BIM collaboration processes. Furthermore, it assisted in the development of a preliminary theoretical framework, which was later modified according to the research findings (Andrade, 2009; Jabareen, 2009). In order to address both high-level aspects and low-level aspects of the design process (Zerjav et al., 2013), a high level IDEF0 process model, and its decomposition were developed based on the RIBA Plan of Work 2013. This model is discussed in detail in a paper that has been published at the *6th CECAR (Civil Engineering Conference in the Asian Region),* which took place in August (20-22) 2013, in Jakarta (Indonesia) (see Appendix A).

So as to create the preliminary research framework for the components of SBD, inductive content analysis was implemented for describing and quantifying phenomena (Elo and Kyngäs, 2008). This is considered appropriate for unstructured data such as findings from a literature survey (Krippendorff, 2012). It is assumed that when classified into the same categories, words, and phrases share the same meaning (Cavanagh, 1997). This feature is particularly useful for creating a standardised process for BIM-enabled SBD implementation. Inductive content analysis includes open coding, creating categories, and abstraction (Elo and Kyngäs, 2008). Open coding means that notes and headings are written in the text while reading it. After this open coding, the lists of categories are grouped under headings that are classified as "*belonging*" (Burnard, 1991; Elo and Kyngäs, 2008; McCain, 1988). Then, a general description of the research topic is generated through abstraction (Burnard, 1991; Robson, 1993). Each category is named using content-characteristic words. Subcategories with similar events and incidents are grouped together as categories, and then, these categories are grouped as main categories (Dey, 1993; Elo and Kyngäs, 2008; Robson, 1993).

However, content validation requires the use of a panel of experts to support concept production or coding issues (Graneheim and Lundman, 2004). The first set of in-depth interviews served to validate the preliminary process model and its categories. As a part of theory-guided analysis (Kohlbacher, 2006), this framework was constantly compared with data, and revised, during the four sets of data collection (Phases 2 and 3), *"iterating towards a theory which closely fits the data"* (Eisenhardt, 1989). This is an essential feature of theory-building; the comparison of the emergent concepts, theory, or hypotheses with the extant literature (Kohlbacher, 2006).

4.7.1.2. Phase 1-B: First set of interviews

This next step contained both deductive and inductive parts, which have served to verify the concept of the developed process model by performing in-depth interviews so as to validate and inform the model. The purpose of the exploratory interviews, during Phase 1 of the research, was to understand whether the concept of a standardised process for SBD fits within the existing business processes. It was decided that the profiles of the interviewees had to comply with the following conditions (theoretical sampling): (i) be an RIBA chartered architect; (ii) undertake sustainable design; and (iii) utilise BIM in practice. For pragmatic reasons, the first choice was contacting organisations in the East Midlands (UK). The contact details of the sample were found though the RIBA Directory of UK Chartered Practices. During the search, only the practices that offered both BIM and sustainable design services were selected. The other method of approach was a more personal one; this was proven to be the most effective. It consisted of contacting people in attended webinars, or introduced by a common contact. If there was no reply to the first email, a reminder was sent after 10-15 days. Out of the 51 people contacted, seven responded, but only five managed to conduct an interview (a response rate of 9.8 per cent). The interviews were conducted though phone conversation (two interviews), Skype conference (two interviews), and in person (one interview). The length of the interviews varied from one to two and a half hours. The interviews were recorded, upon participant's permission, utilising MP3 Skype Recorder (Nikiforov, 2016) software (Skype interviews), and Samsung Galaxy smartphone recorder (face-to-face interview). Following that, the interviews were transcribed utilising Microsoft Media Player (audio), and Microsoft Word (text). These methods were considered to be the most efficient in terms of time and cost. This opportunistic approach to sample selection revealed the significant gap of relevant expertise in the UK construction industry. The interviewees' profiles, for Phase 1, are presented in Table 4.6.

Table 4.6 Profiles of interviewees (Phase 1)

Interviewee - Number	*Design experience*	*National Classification of organization*	*Types of construction Projects*	*Size of Projects (cost)*	*BIM maturity*
I-1	17 years	Medium	Industrial, commercial, workplace, education, residential, healthcare	£1 to £50 million	Level 1 (Microstation, AECOsim)
I-2	19 years	Medium	School, leisure, transport, commercial, master plans, military defense work, residential	£1 to £50 million	Level 1 (Autodesk Revit)
I-3	16 years	SME (small and medium enterprises)	Higher education, primary education, nursery, housing	£0.5 to £20 million	Level 2 (Autodesk Revit)
I-4	16 years	SME	Education, public, housing, health	£0.5 to £20 million	Level 2 (Autodesk Revit)
I-5	20 years	Medium	Housing, education, health, sport and leisure	£250k to £38 million	Level 1 (Autodesk Revit)

The funnel approach (Oppenheim, 2000) was implemented and there were four stages to the interviews: (i) the introductory questions; (ii) the transitional questions; (iii) the main questions; and (iv) a closing one (see Appendix B). Initial questions set the context with "*classifying*" questions. The funnel approach to questionnaire design starts off the module with a very broad question and progressively narrows down the scope of the questions until the end, when it comes to some very specific points. Open or free response questions were implemented at this phase; they were not followed by any kind of choice so as to maintain the spontaneity and expressiveness (Oppenheim, 2000). The introductory questions were about some general facts regarding the size of the organisation, and the size and types of projects usually undertaken. The transitional questions themes were:

- experience with BIM and software choices;
- methods for assessing sustainability in a project;
- methods and means of collaboration and communication among stakeholders;
- identified deficiencies in the transition towards BIM processes; and
- main changes in assessing sustainability using BIM.

In the main part of the questionnaire, the IDEF0 diagram was introduced and explained. The interviewees were asked to identify the similarities and differences between current practice and the IDEF0 model, and identify the main changes that were needed so that the model could be implemented in practice. The rest of the questionnaire was divided in sections. Each section included questions for each design stage of the RIBA Plan of Work 2013. The themes of the questions included:

- information requirements for exchange between stakeholders;
- definition of sustainability aspirations and prioritisation of various aspects;
- level of detail of information needed;
- format of inputs and outputs; and
- interaction with the client at each stage.

The final question was about their future aspirations concerning the emerging technologies (such as BIM), and the changes that should/could be made to successfully incorporate those into the existing practices for SBD. This approach has informed the course of the research into the selection of the research focus areas, and the adequate methods for the data collection strategy. The goal was to determine the main activities along with the expected outcomes (products) of the process. It was argued that although the RIBA serves as a general framework, it can be interpreted in various ways, depending on individual values, experience, and expertise.

4.7.1.3. Phase 1-C: Thematic analysis

Thematic analysis was performed to analyse the data from the interviews so as to identify new components and attitudes/perspectives, drivers, barriers, and limitations in the current state of practice (discussed in Chapter 5). A thematic analysis is one that looks across all the data to identify common issues, and the main themes that summarise all the views (Aronson, 1995; Braun and Clarke, 2006). The key stages in the thematic analysis are described below (Aronson, 1995; Bendassolli, 2013; Bowen, 2008; Braun and Clarke, 2006):

- Transcription and annotation of text. By transcribing and reading, initial ideas emerge, and initial observations are noted.
- Developing a coding scheme based on the theoretical framework generated during the literature review, and also based on the initial observations of the previous stage. The same line(s) of data may be coded in several different ways, from very basic codes to categories that reflect broader analytic themes. The transcript excerpts were charted in excel spreadsheets according to the codes. An example is presented in Appendix C. Then, the patterns across the data on the same topic, were made clearer.
- Searching for themes, making them as abstract as possible. Excerpts from the transcripts have been used as examples during analysis.
- Reviewing themes, and refinement of themes.

- The iterative process of collecting, coding, and analysing the triangulated data continued during the first three sets of data collection (until the completion of Phase 2).
- Producing the report aiming to convince the reader of the validity of the arguments.

The exploratory interviews have revealed a variety of problems that exist due to lack of coordination during the implementation of a building project. The main issue was the lack of understanding of sustainability, and the variety of interpretations that hinder setting clear goals from the beginning. Thus, a better definition is necessary, and apart from that, a common route that should be followed by the project team to guide the process (I-3). It was argued that, guidelines for those, who are not specialists in SBD, must be set. The definition should be expanded from just a checklist so as to highlight what the outcome should be, based on experience from implemented projects, and the knowledge of what actually works and what does not. There was mutual agreement, among the interviewees, that a defined route that gives guidelines during each step of the process would be beneficial for designers, not to give them the answers to their design problems, but to indicate the considerations for each decision and stimulate the thinking of the crucial issues for making an informed decision. One of the experts stated that *"a tool that shows in clear way the level of detail needed so as to make a decision on an accurate basis would be really useful"* (I-3). The most recent RIBA Job Book (9th edition, 2013) (RIBA, 2013a) provides descriptions of the activities for each consultant but does not explain the necessary links between neither them, nor with parts of the process (I-4). The inputs and outputs are described in a generic fashion, and it is not specified which information is critical for each decision, so it remains open to interpretation. Another objection was that sustainability is not part of the core objectives, but is treated as an add-on checklist in the process. Sustainability considerations should be integrated within the main process concurrently along with every other issue (I-4). In addition, the milestones of the process are not specified, they are limited to design reports and information exchanges at the end of each design stage: *"It (the Plan of Work) should* *identify at what stage in a project it is crucial to make sustainability decisions because it obviously makes it more costly and more difficult to do afterwards"* (I-3).

The evidence from the interviews have revealed that while in theory nD modelling has been made possible by the technological advancements, in practice, it is not effectively implemented in a holistic way for SBD. Due to the fragmented way of working, the existing building design process does not effectively permit the integration of sustainability considerations from the early stages, hence, compromising the achievement of sustainability objectives. Advanced ICT offer a significant potential to develop an integrated SBD process with robust BPA, but re-thinking of the existing design process is required. To make a step forward towards Sustainable Development (SD), assisted by the new technological improvements (software, hardware, and networks), there is the need to specify the components and processes of BPA within BIM collaboration. The experts highlighted the need for a commonly defined process, based on lessons learnt, which guides BIM-enabled SBD.

4.7.2. Phase 2: Main data collection and analysis

Based on the findings of Phase 1, the research questions, and strategy, were shaped more clearly. The goal of Phase 2 was to define the components of SBD explicitly, and identify the optimal relationships between them, based on lessons learnt from the best practices. For this purpose, an abductive approach was implemented using multiple case studies, as described in Section 4.4. Following the abductive principle, the hypothesis was tested using both Deduction and Induction (Peirce, 1955). According to Abduction, the researcher does not start with a blank state manner, as implied by the Inductivists. This process has also been characterised as the *"normal research cycle"* (Meredith, 1993). Throughout this iterative process, descriptive models are expanded into explanatory frameworks, which are tested against reality until they are eventually developed into theories, as research study builds upon research study. The result is to validate and add confidence to previous findings, or else invalidate them and force researchers to develop more valid or more complete theories (Meredith, 1993). The following sub-Sections describe the techniques implemented for data collection and analysis during Phase 2.

4.7.2.1. Phase 2-A: Second set of interviews

The first step of Phase 2 was an inductive one, performing six semi-structured in-depth interviews with industry experts. The first two interviews were conducted with participants of the previous stage (Phase 1), who had previously been identified as experts in BIM-enabled SBD implementation. Those interviews also served as pilots for the method (Yin, 2013). Interviews are considered the *"most important sources of case study information"* (Kohlbacher, 2006). Case study interviews are open-ended in nature, permitting the researcher to ask key respondents about the facts as well as their opinions about events (Yin, 2013).

The structure of the interviews, during Phase 2, consisted of four parts: (i) introductory questions, (ii) transitional questions, (iii) main questions, and (iv) reflection and concluding remarks (see Appendix B). The introductory questions followed a structured approach where the researcher asked the same questions in the same way. The transitional and main questions followed a semi-structured approach where a series of open-ended questions were asked. These defined the topic under investigation, and provided opportunities for in-depth discussion. When an insufficient response was provided, the interviewer provided cues and prompts so as to clarify the interviewee's answer. At the end of each interview, the researcher engaged in unstructured dialog based on the answers provided. This dialog presented the opportunity to investigate new emerging themes that had not been included or expected in the initial plan of the interview. The questions had been checked so as to avoid (Knox and Burkard, 2009; Rowley, 2012): (i) leading or have implicit assumptions; (ii) include two questions in one; (iii) invite "*yes/no*" answers; (iv) being too vague or general; and (v) being, in any sense, invasive. Furthermore, the process of shaping the questions was iterative from one interview to the next. This means that questions that were not effective were dropped, while new ones were added, based on new themes (DiCicco-Bloom and Crabtree, 2006). Unplanned follow-up questions were implemented as well, depending on the interviewee's answer, in order to obtain optimal responses from participants (Turner, 2010).

The Critical Decision Method (CDM) (Klein et al., 1989) was implemented for the main questions. The applications of the CDM have been the development and/or evaluation of experts systems, and the identification of training requirements. The method distinguishes the "*expert*" and "*novice*" practitioner, regarding their skills and experience. This happens by focusing on a specific incident (case-based approach), and using semi-structured probing to adjust timing and wording to adapt the case. The method is based on the Critical Incident Technique (CIT) (Flanagan, 1954; Hughes et al., 2007; Woolsey, 1986), which is an accepted method in management research to measure the quality of coordination (Butterfield et al., 2005; Johnston, 2005; Kaulio, 2008). Utilising this method the researcher collected factual information based on real incident narratives, and then, attitudinal data during the incident's reflection. The procedure of the CDM follows six steps (Klein et al., 1989):

i. Select incident to demonstrate non-routine aspects of a domain. The focus was on cases that presented a unique level of challenge for the individual. The experts were asked to select an incident that had a significant effect on the sustainability outcome of a certified sustainable non-domestic building that BIM software was utilised. The follow-up questions included obtaining the details of the case study such as location, timeframe, and duration of the process, floor area, year of completion, and stakeholders that participated in the incident.
ii. Obtain unstructured incident account. Description of incident was obtained in order to build context, understand unique perspective, activate memory, and achieve cooperation. Additional questions were asked regarding the sustainability objectives (both included in the brief and individual ones), and the methods that were used for BPA assessment.
iii. Construct incident timeline. The interviewees were asked to specify the sequence of events that took place during the incident. That included the interactions with other project participants, artefacts, and content of information exchanges.
iv. Identify decision points. At this stage, the interviewee was asked to identify the specific decision points in the process when different design options were

considered. That included asking about how alternative solutions were assessed in order to take one out of several courses of action that affected the sustainable building outcome.

v. Probe decision points. The focus of this stage was to elicit the details to represent the information that was needed at each event time, or recall prior experiences' analogues. The experts were asked to specify their goals (and assessment methods) at the time, along with the options for each decision (choices made or rejected). The basis for selecting an option was requested, and whether a rule was used. Any other types of constraints that took place during the design process were also requested.

vi. Reflect on incident. This probe focused on the lessons learned from the experience, and asked the expert to make suggestions about what should have been done in order to prevent the unwanted outcomes in order to achieve a more sustainable building.

A protocol was followed for performing the interviews that included the following elements (McNamara, 2009; Partington, 2001; Turner, 2010): (i) an environment with little distraction was chosen; (ii) the purpose of the interview was explained; (iii) anonymity and confidentiality were addressed; (iv) the participants were asked if they had any questions (before the interview and at the end of it); (v) permission to record the interview was asked, and once obtained, the recording started (Samsung Galaxy Note 3 smartphone); (vi) the researcher kept notes while the participants were speaking and those guided the prompts for the follow-up questions; (vii) the recorder was verified occasionally to ensure its function; (viii) in order to build empathy, and rapport, the most significant points made by the interviewees were restated by the researcher, and occasional *"uh huhs"* and nods encouraged the responses; (ix) the participants were thanked at the end for their help, and asked if they would like to know more regarding the research outcome, and whether they were willing to answer follow-up questions in the future; and (x) finally, the participants were asked to nominate colleagues or collaborators that fulfil the research criteria (snowball sampling method) (Baker and Edwards, 2012; Davies and Dodd, 2002; Ritchie et al., 2013).

The interviews were of different kinds, regarding the means of communication between the researcher and participants. These included phone, face-to-face, Skype, and email (for follow-up questions only). The reason for these choices was mainly convenience of the participants, but also, restrictions in travel costs and time (Baker and Edwards, 2012). While some researchers have stated that face-to-face interviews have advantage over telephone interviews, others have found it to be encouraging for participants who prioritise anonymity (Sturges and Hanrahan, 2004). Nevertheless, phone interviews have been very common for qualitative research (Knox and Burkard, 2009), and have been found to be more effective in maximising response rate (Tausig and Freeman, 1988). Furthermore, telephone interviews have been found to have the same depth of response as the face-to-face ones (Sturges and Hanrahan, 2004).

It has been argued that one of the case study's strengths is its ability to deal with a full variety of evidence such as documents, artefacts, interviews, and observations (Yin, 2013). Observational data have also been kept in the notes, as well as the interviews' transcripts, in order to overcome the discrepancies between what people say and what they mean. These have included emphasis, or irony etc. Other sources of information were documents regarding the cases studies (Hoepfl, 1997). These have served to triangulate the interviewees' claims with hard evidence so as to strengthen the argument.

4.7.2.2. Phase 2-B: Analysing the second set

The data collected during the second set of interviews were transcribed verbatim, including timings, observations, and comments of the researcher. This strategy has been claimed to improve rigor (Oliver et al., 2005; Poland, 1995). For very rare occasions, parts of the interviews were falling outside the research scope; for those, a summary of their content was transcribed instead. Content and thematic analyses were the first steps performed in order to revise the existing framework and coding system, and identify new themes. The goal was to define the components of SBD, and determine the boundary criteria of the research (Meredith, 1993) along with detecting the existence of conceptual links among the codes of BIM-enabled SBD

(Andrade, 2009; Dey, 1999). Triangulation with existing literature was occurring simultaneously with the analyses so as to enhance internal validity, generalizability, and theoretical level of the theory-building process (Eisenhardt, 1989).

Yin (2013) has suggested five techniques for analysing case studies: (i) pattern matching, (ii) explanation building, (iii) time-series analysis, (iv) logic models, and (v) cross-case synthesis. For the following part, narrative analysis of the incidents collected with CDM was implemented so as to map the process of BIM-enabled SBD utilising structured diagramming techniques. Narrative analysis has been defined as (Schutt, 2011): *"A form of qualitative analysis in which the analyst focuses on how respondents impose order on the flow of experience in their lives and thus make sense of events and actions in which they have participated."*. This concept is widely accepted in organisational research (Myers, 1997), where *"small events in the group history can channel the group in ways that are prospectively unpredictable, though they may appear sensible, even obvious, retrospectively in a qualitative or narrative analysis"* (Stiles, 1993). Thus, a commonly defined process for SBD, can translate the lessons learned through these experiences so as to provide quality assurance and minimise risk for future projects. The observed events from the narratives were the interpretations of reality according to the different perspectives of the experts' disciplines interviewed. In order to synthesise those views, the researcher went through a process where some details were *"sacrificed, selected, emphasized, sequenced, and viewed from different angles, all in an attempt to illuminate reality*" (Stiles, 1993). To achieve that, the coding strategy started with reading the stories and classifying them into general patterns (Schutt, 2011). Flowcharts (see Appendix C) were created in the beginning so as to generate quick interpretations of the data. After the first iteration of analysis, the processes, and sub-processes, were mapped utilising the IDEF3 technique. As a result, common themes that are applicable to new-built non-domestic buildings emerged. The outcome of this task was an initial holistic IDEF3 process model, and some of its decompositions. More importantly, this analysis served to identify the gaps that existed in the understanding of the SBD process. This finding has shaped the design strategy further so as to generate even more targeted questions for the next set of data collection. The outcomes of these analyses have been published in an article in the *International Journal of Energy Sector Management 8 (4), 562-587,* in 2014 (see Appendix A).

4.7.2.3. Phase 2-C: Third set of interviews

The following step was iterative, both deductive and inductive. The goals of this phase were to validate the developed IDEF model, as well as to bridge the gaps in the understanding of the SBD process to that date. Fourteen (14) semi-structured interviews were performed, following the same protocol that took place for the second set of interviews. What was different this time was that the IDEF3 process model was used as a guide during the interviews. The components (Units of Behaviour, Objects, Decision points) and interdependencies were validated by the incident narratives utilising the CDM. Although, the IDEF3 process model itself was not presented to the interviewees at that time, for practical reasons as well as to avoid bias, the researcher's probes followed the model's structure to ensure its validity (predictive theory testing).

As discussed in Section 4.4.4, the data collection continued until no more information, related to the research questions, was provided by the experts so as to reach theoretical saturation (Baker and Edwards, 2012; Glaser and Strauss, 2009; Seale, 1999), which means information replication/redundancy (Bowen, 2008; Patton, 2002), or *"theoretical sufficiency"* (Andrade, 2009). While originally developed within grounded theory, theoretical saturation, has currently evolved its meaning to accommodate the other types of qualitative research (O'Reilly and Parker, 2012). This method implies that data collection and analysis are happening concurrently (iteratively) at this phase (DiCicco-Bloom and Crabtree, 2006). For this research project, information redundancy was defined as the point when a researcher had heard the same thing over and over again (Sandelowski, 1995) and the regularities among the data were made clear (Bowen, 2008; Hoepfl, 1997). Moreover, *"pattern matching"* (Eisenhardt, 1989; Hyde, 2000; Yin, 2013), iterative alternation of induction and deduction between the IDEF model's predictions and the incidents' narratives, has assisted in formalising the components' relationships. The complete process model, before the final validation and refinement (discussed in

Chapter 7), can be found in Appendix D. Part of the research outcomes (framework and model) have been published in an article in the *Architectural Engineering and Design Management (AEDM)* journal, in August 2016 (see Appendix A).

4.7.3. Phase 3: Validation stage

Based on the developed theory, the BIM-enabled SBD process can be defined, and structured using the IDEF diagramming techniques. What is more, the findings from the interviews and existing theories, have revealed the need for process automation. Thus, a software tool (Green BIM Box, GBB), discussed in Chapter 6 (Section 6.4), has been conceptualised by the researcher as a recommendation, and the behaviour of the system's architecture is demonstrated through OMG UML Sequence Diagrams. A mock-up of the user interface of GBB has been developed using Lumzy (Crunch Frog, 2010-2015) online prototyping application, which enables the development of quick demonstrations of concepts. Nevertheless, the mock-up created lacks extensiveness (limited number of elements can be added), and reliability (categories have been disappearing during presentation). The following sub-Sections describe the process to validate the final framework and the process model, along with the concept of automating the repeatable administrative tasks of the BIM-enabled SBD process. The validation process, and results obtained, are discussed in Chapter 7 in more detail.

4.7.3.1. Phase 3-A: Pilot workshops with peers

As discussed in Section 4.5, the theory was tested both quantitatively and qualitatively utilising structured questionnaires (King, 1994). The questionnaire was split into three parts (see Appendix B): (i) the first one contained introductory questions regarding the participants' background and experience; (ii) the second one requested information regarding the implementation of SBD, as well as attitudes to statements; and (iii) the third part asked for feedback on the GBB tool's demonstration. The questionnaire consisted of a mix of multiple choice questions, attitudinal questions, and critical questions that provided in depth understanding.

The next step was to conduct a pilot survey for checking that the questions were clear, so as to make the necessary changes accordingly (Rowley, 2012; Yin, 2013).

Two internal validation workshops with peers, experts in SBD (8 participants), suggested no significant alterations to the theory or the tool's concept. Positive feedback was received overall. Whenever instances of inconsistent or controversial answers occurred, the researcher followed-up with the participants in order to resolve the issue. The third section of the questionnaire was found to be problematic due to the fact that the participants were not able to interact with GBB. Their answers were less confident regarding their ability to comment on GBB, since their perceptions were based on a video demonstration of the tool. However, the software tool's functionality is a limitation that could not be overcome, within the scope of the PhD project, due to the lack of resources (time, and advanced programming skills). On the other hand, the participants found the concept to be interesting and useful.

4.7.3.2. Phase 3-B: Interviews with industry practitioners

Amendments to the method of validation were made, based on the feedback provided in the pilot workshops. The content of the first two sections of the questionnaire was found to be appropriate for validating the theoretical framework with industry practitioners (although it needed simplification for time-saving purposes). However, the third section had to be altered, due to the incompleteness of the GBB's demonstration. For this purpose, theory testing by *"pattern matching"* (Hyde, 2000; Yin, 2013) was considered adequate in order to validate part of the IDEF models' sub-processes, and therefore the concept of structuring BIM-enabled SBD. The sample of industry experts was a mix of previous participants as well as new ones so as to strengthen both the internal and external validity of the theory. As a result, seven (7) in-depth interviews with industry practitioners were performed. The methods used, and feedback received, are presented in Chapter 7 in detail, and the interviews' questionnaire and handouts can be found in Appendix B.

4.7.3.3. Phase 3-C: Re-visiting the model and concept

All participants acknowledged the usefulness and feasibility of the process for the implementation of BIM-enabled SBD. Furthermore, the practitioners reviewed the IDEF model's three-level depositions and suggested minor alterations for its improvement. Therefore, the process model has been amended according to the participant's comments. The final refined IDEF process model is presented, and discussed, in Chapter 7 (Section 7.5).

4.7.4. Quality criteria and controls

There are no methodological criteria capable of guaranteeing the absolute accuracy of research (Henwood and Pidgeon, 1992; Schutt, 2011). Nevertheless, a number of good practices have been suggested by qualitative researchers to demonstrate rigour, and enhance the validity and reliability of research. This Section discusses the measures that were considered during this project in order to ensure its quality. Table 4.7 summarises the quality criteria and controls implemented during this study.

Numerous studies have argued the issue of validity and reliability, providing various definitions with overlapping meanings (Guba, 1981; Henwood and Pidgeon, 1992; Johnson, 1997; Kohlbacher, 2006; Krefting, 1991; Riege, 2003; Tracy, 2010). Whetten (1989) has addressed two criteria for a "*good*" theory: (i) comprehensiveness, and (ii) parsimony. Moreover, Yin (2013) has discussed four conditions for testing quality: (i) construct validity, (ii) internal validity, (iii) external validity, and (iv) reliability. The following sub-Sections describe the concepts of validity (construct, internal, and external), and reliability and discuss the measures undertaken during this research to achieve them.

Table 4.7 Summary of quality measures and strategies implemented (Creswell and Miller, 2000; Davies and Dodd, 2002; Golafshani, 2003; Hoepfl, 1997; Kvale, 1994; Malterud, 2001; Merriam, 1995; Riege, 2003; Seale, 1999; Shenton, 2003; Yin, 2013)

Conventional terms (quantitative)	***Naturalistic terms (qualitative)***	***Practices and methods***
Construct validity	• Coherence • Truth value • Factual validity • Confirmability	• Thorough literature review • Multiple sources of evidence (data triangulation, corroboration) • Established chain of evidence • Case study selection • Theoretical sufficiency (saturation) • Member reflexions
Internal validity	• Credibility • Consistency • Interpretive validity • Theoretical validity	• Coding application, data charting • Low inference descriptions • Pattern matching • Explanation building • Logic models
External validity	• Transferability • Applicability	• Theoretical generalisation • Theory testing • Member checking • Peer review (dissemination)
Reliability	• Dependability • Stability • Reproducibility • Accuracy • Sincerity	• Case study protocol • Replication logic through multiple case studies • Extended field work • Sample selection • Transparency • Self-disclosure • Procedural ethics

4.7.4.1. Construct validity

Construct validity is established in relation to existing models, theories, and interpretations, aiming to ensure that the operational measures undertaken are adequate. It is demonstrated by confirming that the data collection process is based on logical assumptions, and that the research maintains consistency from the research questions to conclusions (Yin, 2013). The same concept has also been defined as *"meaningful coherence"* (Tracy, 2010).

Various strategies were implemented to achieve construct validity during this research. A thorough literature review took place throughout the duration of the study to determine the social and cultural context as well as the state of the art (Stiles, 1993). A structured process in interviewing, recording, transcribing and interpreting the data (Lincoln and Guba, 1985), has assisted in establishing a systematic chain of evidence (Yin, 2013). Furthermore, use of multiple sources of evidence (triangulation, corroboration) (Denzin, 1978; Patton, 1990; Seale, 1999), have allowed stronger substantiation of constructs and hypothesis, which have enabled theoretical generalisability. Selection of case study interviewees of varying viewpoints attempted to reduce subjectivity, and ensure confidence in the truth of the findings (Guba, 1981; Stiles, 1993). Conflicting results have been investigated further in order to be resolved (Seale, 1999), so as to increase the factual validity of the data (Johnson, 1997). In addition, theoretical saturation has been argued due to the fact that repetition of information was occurring, confirming what was already known, instead of adding new information to the theory (variables, properties, and relationships) (Dey, 1999; Glaser and Strauss, 1967). Finally, confirmability has been attempted by having key external informants review the findings of the research (Miles and Huberman, 1994; Yin, 2013).

4.7.4.2. Internal validity

In quantitative inquiry, internal validity refers to the extent to which the findings accurately describe reality (Hoepfl, 1997; Kvale, 1994). In qualitative research, credibility depends less on sample size than on the richness of the information gathered, as well as on the analytical abilities of the researcher (Patton, 1990; Tracy, 2010). Thus, consistency, not statistical regularity, improves the confidence in the developed theory (Stiles, 1993). Consistency has been defined as comprehensiveness of the elements, and the relations between elements (Stiles, 1993).

Tactics that have grounded the interpretations of this research were the definitions of categories, transcription, coding, data charting, thematic analysis, and synthesis (Stiles, 1993). Furthermore, low inference descriptions were implemented (the interviews were recorded and transcribed verbatim). As a result, direct quotations have been used to maintain factual accuracy, which means that the viewpoints, thoughts, and intent of the participants have been accurately understood and communicated (Johnson, 1997). Additionally, logic models were developed to demonstrate the relationships of the defined categories. *"Pattern-matching"* (comparing observed pattern with predicted), was performed during the third set of interviews, and is considered a valued tactic to demonstrate the consistency of case study analysis (Andrade, 2009; Guba, 1981; Riege, 2003; Yin, 2013). Theoretical validity, has been obtained where the theoretical explanation developed by the researcher fits the data and *"is therefore credible and defensible"* (Johnson, 1997).

Several techniques have served to demonstrate both construct and internal validity. In this study, triangulation of data and *"member checks",* in which respondents are asked to corroborate findings, have been utilised for testing confirmability. The latter has also been defined as *"testimonial validity"* (Lincoln and Guba, 1985)*,* which is essentially a straightforward check on the interpretation's accuracy. Nevertheless, Riege (2003) has stated that *"credibility involves the approval of research by either interviewees or peers".* Peer reviews have been implemented in this research through publications in conferences and scientific journals (see Appendix A), as well as validation workshops with peers, and interviews with industrial practitioners, during Phase 3 of the research (see Appendix B). The validation outcomes are discussed in Chapter 7 in detail.

4.7.4.3. External validity

In quantitative research, external validity is concerned with expanding the findings to the general. Thus, it is more applicable to test generalisation of statistical samples (Andrade, 2009; Lee and Baskerville, 2003). Contrastingly, case study relies on analytical generalisations where the findings are generalised in some broader theory (Riege, 2003; Walsham, 1995). For theory-building, multiple cases intend to produce theoretical generalisations instead of testing theory (Andrade, 2009). Therefore, transferability is a more appropriate concept to test the quality of the developed theory (Henwood and Pidgeon, 1992; Hoepfl, 1997; Lincoln and Guba, 1985). Design theory, communication theory, organisational theory, and GST have been discussed to help explain the phenomenon of SBD. Moreover, peer review and industrial engagement have disseminated the research findings in order to obtain external feedback so as to test the transferability and applicability of the theory (Guba, 1981; Mishler, 1990; Riege, 2003; Sandelowski, 1993b). For this purpose, journal and conference articles have been produced and published (see Appendix A), and presentations within the university, as well as external organisations have been performed (see Appendix B).

Despite the fact that validation exercises took place during this study, it is important to discuss the fact that several researchers have questioned the need of a separate validation stage within the iterative theory-building process (Drongelen, 2001). Since the development of theory from case studies is an iterative process that ideally leads to saturation (Eisenhardt, 1989), a separate validation stage is not needed. For abductive research, the validation of the theory is integrated within this process (Drongelen, 2001). Validation is considered more appropriate (Eisenhardt, 1989) *"when little is known about a phenomenon, current perspectives seem inadequate because they have little empirical substantiation or they conflict with each other or common sense."* What is more, member checking has been criticised that may even undermine the trustworthiness of a research project (Sandelowski, 1993a). This happens because the panel of experts may have certain personas, personal goals, and different agendas to promote. Whereas the researcher strives to serve multiple realities, the members serve only their own reality. Furthermore, the stories that members tell in interviews are constantly changing, or may not be in the best position to check the accuracy of the account (Sandelowski, 1993a). Other arguments against member checking are that members usually are uninterested in participating in such an exercise and reluctant to disagree with the researcher to minimise conflict. Moreover, different members may have different views to the same interpretation. Sandelowski (1993a) has argued that lack of convergence or consensus does not necessarily invalidate an interpretation. It is argued that validation of a research happens more effectively informally, through daily interactions and dissemination, than in a formal manner through arranged workshops or interviews. Aside from all the above, certainty about the validity of abductive inferences *"cannot be achieved"* (Reichertz, 2004). Using this procedure, the most that can be achieved is a constructed shared truth. Peirce (1955) has suggested that "*all*" includes not only all the members of a society now, but also the ones that will come after. This notion means that the process of checking can never be achieved completely, and thus, absolute certainty is impossible. To conclude, *"infallibility in scientific matters seems to me irresistibly comic"* (Peirce, 1955).

4.7.4.4. Reliability

In quantitative research, reliability refers to the demonstration that the procedures that took place during the research process can be repeated by other researchers to achieve similar findings (King, 1994; Riege, 2003). To achieve that, a transparent detailed research process is a recognized marker of quality (O'Reilly and Parker, 2012). Therefore, presenting the chain of evidence contributes to the trustworthiness of the analysis (Andrade, 2009). Kirk and Miller (1986, cited in Hoepfl, 1997) have identified three types of **r**eliability referred to quantitative research which relate to: (i) the degree to which a measurement, given repeatedly, remains the same; (ii) the stability of a measurement over time; (iii) the similarity of measurements within a given time period. For qualitative research, stability may refer to whether the same results are obtained in a renewed application of the analytical tool to the same text (Kohlbacher, 2006). Also, reproducibility is the extent to which the analysis achieves the same results under different circumstances, for instance with different coders (ibid.). However, from an interpretive approach, the purpose in doing so is not to guarantee that a second researcher will arrive at exactly the same conclusions as the first one might have (Andrade, 2009). Consequently, reliability for qualitative research *“means producing results that can be trusted and establishing findings that are meaningful and interesting to the reader”* (Trauth, 1997) instead of showing consistent results by repeated analyses. Finally, accuracy assumes stability and reproducibility, and denotes the extent to which the analysis meets a particular functional standard (Kohlbacher, 2006).

The techniques to establish reliability during case study research have been the development of a protocol for case studies during data collection, the execution of a protocol during the interviews, and an establishment of a case study database (Eisenhardt, 1989; Merriam, 1988; Parkhe, 1993; Yin, 2013). The consistent responses obtained, along with consistence procedures, have assisted reliability (Riege, 2003; Sandelowski, 1993a). Extended field work and data collection process that lasted for three years, following an iterative process of induction and deduction, have proven consistent in confirming the research findings. Procedural ethics (Tracy, 2010) is another significant measurement of reliability. To address that, the research has obtained a formal ethical review approval from the Ethical subcommittee (Ethical Clearance Checklist form found in Appendix B). Furthermore, information sheets and consent forms have been provided to the participants, and signed (see Appendix B). During the interviews, consent was asked to record the conversation, while during the analysis, coding was implemented to ensure anonymity of the participants (Schutt, 2011). In addition, the data obtained and generated (recordings, transcripts, and documents) have been stored in secure locations so that they are not accessible from outside parties.

As discussed in Section 4.2.3, as opposed to quantitative research, interpretative research is neither value-free, nor objective (King, 1994; Kohlbacher, 2006; Sandelowski, 1986). Therefore, Patton (1990) has advised towards *"empathic neutrality".* To demonstrate neutrality, Lincoln and Guba (1985) have suggested providing and audit trail consisting of (i) raw data; (ii) analysis notes; (iii) reconstruction and synthesis products; (iv) process notes; (v) personal notes; and (vi) preliminary developmental information. Tracy (2010) has argued that resonance, and sincerity enhance reliability. To achieve that, reflexive journals have been created from the beginning of the study to map the process of exploration and for self-reflection, as the researcher's understanding has shaped progressively (Ortlipp, 2008). Additionally, in Section 4.2.3, the researcher's biases and beliefs have been expressed in an effort to set them aside (Finlay, 2002). That includes the researcher stating their prior experiences and standing point, which affect their perspective of interpreting and analysing the data (Schutt, 2011). It is believed that (Stiles, 1993): *"The strategy of revealing rather than avoiding involvement is consistent with the broader shift in goals from the truth of the statements to the understanding by participants and readers."*

4.8. Summary

This Chapter has discussed the methodology adopted for this PhD research project. It has presented the philosophical foundations of the pragmatic abductive research approach, and an iterative theory-building process for case study research. Methods and techniques implemented, for data collection, have included semi-structured interviews, documents, workshops, and structured questionnaires (mixed methods). Structured diagramming techniques have been used to map the SBD process (IDEF0, IDEF3, and UML), and to describe the developed conceptual tool (GBB). A chronological account of the research design has been presented, split into three Phases (1-3). The sequential and simultaneous processes of data collection and analysis, have been made explicit. In addition, the quality criteria and controls considered to achieve credibility and trustworthiness, have been rationalised. Table 4.8 summarises the research design implemented.

The following Chapters (5-7) analyse the research findings, which fulfil the research aim and objectives (presented in Chapter 1), by implementing the methodological approach discussed this Chapter. Figure 4.9 illustrates the PhD research process and outcomes.

Table 4.8 Summary of research design

Philosophy	Realism/Pragmatism	No commitment towards a specific system (Positivism or Constructivism).
Reasoning	Abductive	Iterative process of induction and deduction.
Strategy	Multiple case studies	In depth exploration of a situation. Emphasis on understanding processes, and the standpoints of participants, in their context.
Data collection methods	Semi-structured interviews, documents, workshops, and structured questionnaires	Both qualitative and quantitative methods to strengthen the study.
Data analysis methods	Content analysis, thematic analysis, pattern-matching, diagramming techniques	Iterative theory-building process comprised of three phases (exploratory, main, and validation stage).
Quality measures	Validity (construct, internal, and external), reliability	Thorough literature review, theoretical sufficiency, low inference descriptions, theoretical generalisation, member checking, peer review, extended field work, transparency, self-disclosure, procedural ethics.

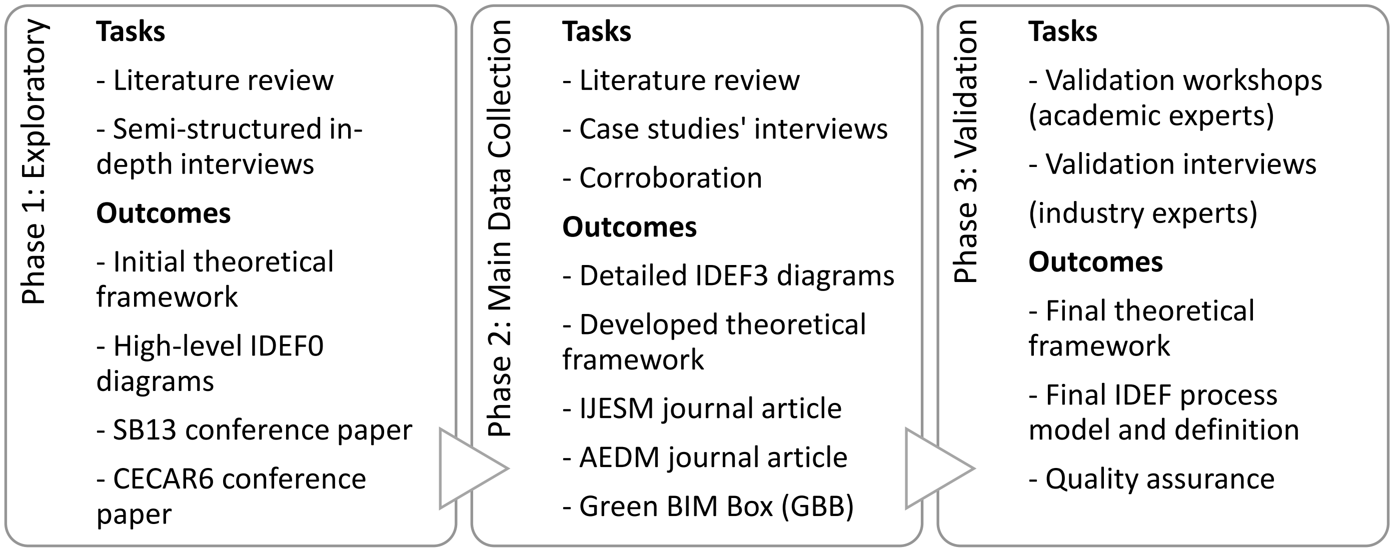


Figure 4.9 The PhD research process and outcomes

Chapter 5

Development of BIM-enabled SBD process framework

5.1. Introduction

This Chapter presents the framework of components that constitute the BIM-enabled SBD process. First, the components have been identified, and defined, utilising content analysis (Elo and Kyngäs, 2008) and thematic analysis (Braun and Clarke, 2006) to demonstrate the opportunities, challenges, and limitations for the implementation of BIM-enabled SBD, utilising the existing technological enablers (e.g. BIM, BPA, ICT). Then, in Chapter 6, the SBD components are coordinated based on narratives of case studies' incidents utilising the CDM (Klein et al., 1989). Figure 5.1 illustrates the three levels of abstraction considered during the data analysis. "*BIM-enabled Sustainable Design Process*" is the main category of the classification. "*Roles*", "*Tasks*", "*Deliverables*", and "*Decision points*" are the generic categories of the framework. "*Contractual agreements*" is an example of a sub-category of the generic category "*Role*s". First, the Chapter clarifies the project team's roles and responsibilities towards SBD (Section 5.2), followed by the SBD tasks delegated to each role (Section 5.3), and their deliverables for BIM-enabled SBD (Section 5.4). The implications of strategic project management to the design programme, are explored in Section 5.5. Then, the current approaches to the planning and delivery of SBD, along with the attitudes towards a structured collaborative process, are discussed in Section 5.6. Finally, Section 5.7 summarises the main arguments reported in this Chapter. Excerpts from the transcripts have been quoted throughout so as to maintain factual accuracy as much as possible, and thus, strengthening the internal validity of the analysis.

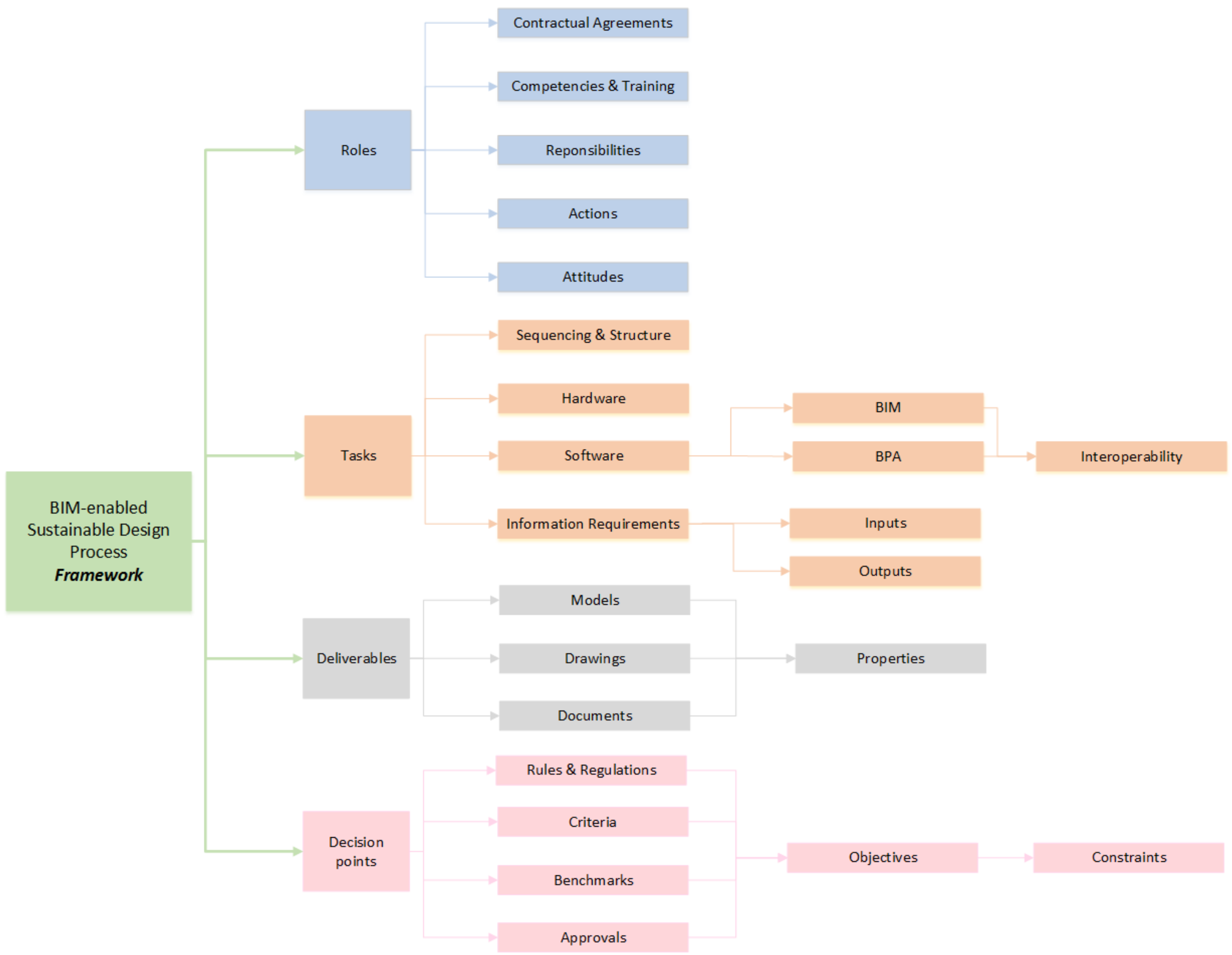


Figure 5.1 BIM-enabled SBD process framework

5.2. Roles, responsibilities, and competencies

Sinclair (2013) has argued that regardless the form of procurement, specialist subcontractors' roles have become increasingly important, adding that: *"their involvement must be clearly defined early on".* Given the requirements of multidisciplinary collaboration for SBD, specialised roles, and their responsibilities are essential. Although new roles have already been identified to accommodate the core BIM uses (Barnes and Davies 2014), the SBD roles have not been sufficiently defined yet (see Sinclair 2013; Barlow 2011). In addition to the traditional roles (e.g. client, architect, structural engineer), specialist roles from a range of expertise are required, including: BIM manager, BIM information manager, BIM coordinator, BPA specialist, and Sustainability Consultant. The following sub-Sections present the findings, and define the roles required for efficient SBD implementation.

5.2.1. Definition of SBD roles

The collaborative project team needs to be established at RIBA Stages 0 "*Strategic Definition*" and 1 "*Preparation and Brief*" (Sharp et al., 1999; Sinclair, 2013; RIBA, 2013a). A comprehensive account of roles' responsibilities has been provided by an Interviewee (BREEAM Assessor/Sustainability Engineer) in the form of an "*action list*". Furthermore, the information provided has been crosschecked, and enriched, by the rest of the Interviewees' transcripts. As a result, this research has identified the main roles and responsibilities for SBD, presented in Table 5.1. Adoption of a common language for job titles, descriptions, and responsibilities would lead to clear objectives for the project management of sustainable buildings.

Table 5.1 Roles and responsibilities for sustainable building design (early stages)

- **Client/Client Adviser:** Selection of site; commissioning; consultation with stakeholders; possibility of shared facilities; security; proximity to amenities and public transport; responsible sourcing of materials; maximum car parking efficiency; energy efficient equipment.
- **Architect/Lead Designer**: Site investigation; shared facilities; security; amenities; recyclable waste; daylight; view out; glare control; building fabric performance and infiltration; material specification; re-use of building fabric and structure; responsible sourcing of materials; insulation; daylighting; hard landscaping.
- **Landscape Architect/Ecologist:** Site investigation; ecological value protection; re-use of land; enhancing ecology; outdoor space; hard landscaping, and boundary protection.
- **MEP (Mechanical, Electrical, and Plumbing services) Engineer:** Site investigation; community energy supply; low and zero carbon technologies; daylighting; internal and external lighting levels; lighting zones and controls; potential for natural ventilation; indoor air quality; thermal comfort; thermal zoning; reduction of CO_2 (carbon dioxide) emissions; building fabric performance and infiltration; free cooling; water consumption; NOx (nitric oxide and nitrogen dioxide) emissions.
- **Structural Engineer:** Site investigation; re-use of building façade and structure; recycled aggregates.
- **Civil Engineer:** Site investigation; water management; irrigation systems; flood risk.
- **Geotechnical Engineer:** Site investigation; re-use of land; contaminated land.
- **Transport consultant:** Site investigation; provision of public transport; travel plan; maximum car park capacity.
- **Cost Consultant:** CapEx (Capital Expenditure); OpEx (Operational Expenditure); Lifecycle cost assessment.
- **Contractor:** Site investigation; construction site impacts; CCS (considerate contractors) compliance; construction site waste management; construction waste management.
- **Sustainability Lead/Consultant:** Site investigation; sustainability briefing; client consultation; developing schemes for the potential building; coordinating different stakeholders; providing advice regarding material specifications, saving water and energy; social and environmental impact.
- **Sustainability Engineer/Energy Modeller:** Energy modelling; thermal environment modelling; ventilation modelling using CFD (Computational fluid dynamics); lighting modelling.
- **Lighting Engineer:** Daylight analysis assessment; design and implementation of artificial lighting arrangements.
- **BREEAM/Passivhaus Assessor:** Client consultation; follow the BREEAM/Passivhaus routes, planning statements; coordinating different stakeholders; assess evidence from the design team; providing advice; getting the certificate.
- **Acoustician:** Site investigation; noise attenuation; inside acoustic performance.
- **Public Health Consultant:** Site investigation; flood risk; water recycling; irrigation systems; watercourse pollution.
- **BIM Manager/Coordinator:** Develop BIM strategy; assist the team with software selection and interoperability; determine information exchanges; develop BEP; coordinate BIM models and information (4D, 5D); review model and detect clashes; report clashes; resolve areas of uncertainty in the model; general overview that the BEP is followed as planned.

The Interviewees argued that the Sustainability Lead/Consultant needs to be appointed from RIBA stage 0. Understanding of sustainability is needed in order to make architectural design decisions from the beginning of the project. Thus, the Architects either need to undertake training to understand these concepts, or employ someone to advise them at stage 0. The excerpts below comment on this issue:

> *"Our main duty is to LEAD [emphasis] the design and ensure sustainability is an integral part of it. Sustainability analysis would be undertaken by other members of the design team." (Architect)*

> *"Five, six years ago we would have employed an external sustainability consultant right from the beginning of the project to give a broad assessment across all areas of sustainability. The last six years we have moved away from that really, we can do a lot of assessment ourselves… for a different project there may be new challenges, then we DO [emphasis] employ a consultant to look specifically into sustainability." (CS1/Architect)*

It has been noted by the Sustainability Engineers that consultation directly with the Client, at the briefing stage of design, has currently become a lot more common. An Interviewee (CS3/Architect/Sustainability Consultant) described that when the Client had clear sustainability aspirations, a Sustainability Engineer performed early calculations for feasibility (e.g. climate analysis, site analysis) even before Briefing (RIBA stage 1) started. Sustainability assessment should begin from the first instance of design conceptualisation as an integral part of the process in order to meet the current building regulations, and to avoid waste of time and money due to rework. The excerpt below demonstrates the experts' attitude:

> *"Traditionally, years ago, we were appointed by the architect, once they have almost won the competition and that's too late to have any influence on the design … They want an Energy Statement and a Sustainability Statement right up front and you can try to get it at this stage, to see if there is feasibility. Because they need to know … the planning rules and the regulations mean you've got to do stuff much earlier on, which is building engineering and environment at the early stage in the design ... They say, we need some input*

much earlier on, so we don't waste money." (CS13/Sustainability Director/Engineer)

The findings show that the best practices avoid fragmentation of roles; the core design roles strive to acquire new skills and resources (e.g. hardware specifications, BPA software licenses) so as to perform BPA. As a result, the Architect/Lead Designer frequently undertakes the role of the Sustainability Consultant as well and, in certain cases, they were able to perform the preliminary BPA themselves, as Passivhaus Assessors (for CS1, CS2, and CS3). In addition, it was supported that the architectural design team should also include the BIM Manager/Coordinator, or even, a Coordination Team for large projects (e.g. CS7, CS8). Furthermore, the MEP Engineer frequently undertakes the role of the Sustainability Engineer, as well as the role of the BREEAM Assessor. In certain cases, it has been revealed that, they also undertake the role of the Sustainability Lead (i.e. CS2, CS4, and CS9).

5.2.2. Competence assessment

For selecting the appropriate design team members, the following considerations need to take place during strategic definition and briefing (RIBA stages 0 and 1):

- **Is the organisation Level 2 BIM Certified?** BRE has developed a "*BIM Level 2 Certificated Practitioner Scheme*" for members to demonstrate compliance with the requirements of BIM Level 2 maturity (Building Research Establishment Ltd, 2015). An Interviewee (CS10/Architect) described their organisation as certified. Despite that fact, it was found that the sustainability aspects of design implementation still followed ad hoc processes.
- **Do the organisations have licences for BIM and BPA software tools?** Checking compatibility between versions of BIM software tools and BPA tools is vital for a seamless process (Yu, 2014). An Interviewee (CS4/Architect) described a process where the BIM Manager was responsible for coordinating the team and bringing together the outputs of software tools. The technology strategy and interoperability between software tools are discussed in Section 5.3 in detail.

- **Is the hardware adequate?** BIM software tools as wells as BPA need certain hardware components to be present in the computer. The minimum system requirements guidelines of the selected software should be reviewed in advanced. An Interviewee (CS14/Sustainability Engineer/BREEAM Assessor) reported problems between IES-VE and laptop computers that have been inadequate for running simulations. For exchanging data, the selection of intranet or/and extranet must be determined; the internet connection speed is also important in the latter.
- **Are the Project Team's members able to utilise BIM software?** For the core disciplines (i.e. Architect, Structural Engineer, and MEP Engineer) the CAD competences needed are the following: (i) modelling, (ii) linking information, (iii) downloading elements from supplier's databases. The BIM Coordinator needs to be able to review all disciplines models. An Interviewee (CS7/ BIM Coordinator) described utilising Navisworks although he reported that Solibri has more capabilities to perform tasks efficiently. The limitation, in that case, was the lack of training and confidence to use the software. Interviewees (Sustainability Engineer, CS14/BREEAM Assessor) stated that the BIM model is very useful solely as an information resource to perform BPA. However, another Interviewee (CS9/Sustainability Engineer/BREEAM Assessor) stated that they find the new technology (BIM) intimidating, and as a result, required receiving information solely in 2D drawings. Another Interviewee (CS13/Sustainability Director) highlighted that the lack of time to do the necessary training so as to change their collaborative processes. In order to eliminate bottlenecks in the process, the design team needs to be selected carefully; by having clear goals from the beginning, regarding the competence needed or whether time permits further training. The following excerpt illuminates the issues discussed above:

"What you need to do is to train the whole staff to be able to use the new method. This thing is extremely difficult and there is no time to do that. You cannot say "we freeze all our projects to train for a week", you cannot do that. The obvious thing is that it should happen in different stages. On the other hand,

if only five people out of hundreds are able to use it, it does not help either. If I develop a model in a new programme that is fantastic and no other person can use it, then it is useless. We tried to implement BIM here and we couldn't make it work. We had to abandon that because of the project deadlines and lack of time." (CS14/Sustainability Engineer)

Qian (2012) has discussed that although BIM is not a panacea for the lack of productivity, it can ultimately improve efficiency in the long run, if adequate processes get developed for its implementation. Furthermore, Giel and Issa (2011) have demonstrated that BIM is a worthy investment for the owner. Therefore, it is recommended that careful consideration of the existing working process is required in order to make the necessary changes.

- **Are the Project Team members knowledgeable about sustainability? Are they able to utilise BPA software and interpret the results?** The Sustainability Consultant/Lead and the Sustainability Engineer roles have been introduced in the previous Section (5.2.1). Both roles need to have an understanding of the basic concepts of environmental physics, building performance, and the factors that affect human comfort. On one hand, the Sustainability Consultant needs to show a holistic understanding of Sustainable Development (SD), and how its theory and principles can be applied to practical problems. Interdisciplinary understanding of sustainability is necessary to be able to identify the key parties involved for each type of project and their roles in the delivery of sustainably performing buildings. On the other hand, the Sustainability Engineer needs to demonstrate problem-solving capabilities based on numerical and graphical procedures. They need to operate complex dynamic simulation software (e.g. IES-VE), interpret the results, and generate reasonable recommendations from the simulations. The aspects of the analysis include climate and site assessment (e.g. availability of sun, light and wind). This role performs feasibility studies for different building design strategies in order to assess their environmental performance. Furthermore, they should be able to evaluate daylighting, heating, and cooling strategies, which are adequate to minimise energy demand, and prioritise the use of natural resources, when possible. Moreover, they should be able to propose mechanical services to meet the required loads efficiently. For this reason, this role has usually been undertaken by the MEP Engineers. Nevertheless, passive design implementation has also been performed by Architects specialised in environmental design. Most of the participants that have been interviewed had acquired this knowledge by studying at postgraduate level. For the BREEAM certification scheme, BRE offers a training course especially targeted to prepare practitioners in order to become assessors.

5.2.3. Identifying sustainability aspirations

The "*Plain English Questions*" (see Sinclair, 2013) have been developed so as to understand the Client's aspirations for sustainability (at RIBA stage 0) as well attain the information necessary to be able to quantify and assess sustainability (during RIBA stages 1 and 2). Based on the Client's needs and aspirations, the appointments of sustainability specialists should be made at RIBA stage 0. Combining the findings from the interviews with the literature review survey (see Chapter 2, Section 2.2), there are three pillars for SBD: (i) occupant comfort and health, (ii) environmental impact, and (iii) client satisfaction and approval. An example of the coding of the Interviewees' answers can be found in Appendix C.

Figure 5.2 presents the categories of SBD. The three pillars of SD (Rodriguez 2002), presented in Chapter 2, have been aligned with the requirements that are relevant for SBD. A holistic approach is presented that encompasses the environmental impact, occupant comfort and health, along with the commercial aspects of building design. In order to comprehend the Client's sustainability aspirations, which are relevant to strategic project management for sustainability, the questions are decomposed for each of the categories.

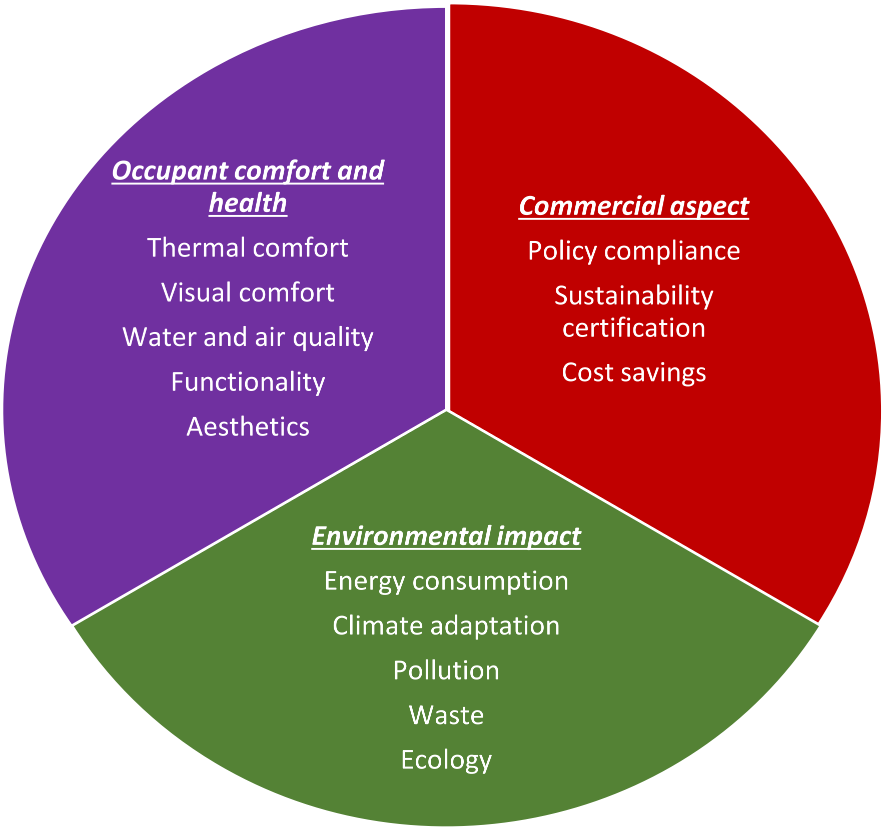


Figure 5.2 Categories of SBD goals

5.2.3.1. Occupant comfort and health

The "*Occupant comfort and health*" aspects are concerned with adapting the building design to better fit the occupants' needs. This category requires the following information during briefing (RIBA stage 1):

- **What types of activities are going to take place in the building?** The designer would have to examine the activity rate (met), and the heat generated by the occupants in terms of magnitude (W) and type (e.g. sensible or latent). CIBSE's Guide A Environmental Design (CIBSE, 2006a) provides values for a wide variety of activities. The Lead Designer and/or Sustainability Lead usually attain this information from the Client or directly from the Occupants.

- **What are the distinct areas of the building? What is their operating schedule?** The operating schedule is critical for environmental design, so as to align simulations with prevailing climatic conditions and hours of daylight. The Lead Designer usually attains this information from the Client or the Occupants.

- **How many people are going to occupy each area the building?** This is a critical consideration because occupancy schedules affect not only functionality, but also thermal comfort and energy performance. The Lead Designer usually attains this information from a Client, who is informed. Otherwise, the Lead Designer needs to perform Occupant studies for this purpose.
- **What equipment is going to be utilised at each building's space?** Apart from considerations such as energy consumption and durability of the selected equipment, the internal heat gains from the use of equipment (including lighting loads) can significantly alter heating and cooling demand. An Interviewee (CS13/Sustainability Director) described this aspect as the most overlooked whilst these considerations can lead to zero carbon buildings. For more accuracy, the Lead Designer usually attains this information from a Client, who is informed. Otherwise, the Lead Designer needs to perform Occupant studies for this purpose (Menezes et al., 2012), or utilise the existing codes' guidelines (e.g. Part L, SAP).
- **What are the individual characteristics of the occupants?** This question is relevant when the occupants belong to groups that have specific needs (such as children or elderly people). Other factors that contribute to this aspect include clothing, state of health, acclimatisation, and gender among others (Andersen et al., 2009; Karjalainen, 2007; Parsons, 2002; Wei et al., 2011). This information is used to determine the assumptions regarding thermal comfort. Methods to determine thermal comfort include the Bioclimatic Chart, SET, Predicted Mean Vote (PMV), and the Adaptive Thermal Comfort approach (discussed in Chapter 2). The Lead Designer usually attains this information from a Client, who is informed, for more accuracy. Otherwise, the Lead Designer needs to perform Occupant studies for this purpose. Alternatively, the designers follow the regulations' guidelines.
- **What are the illuminance levels required for each activity?** The adequacy and suitability of lighting for each activity is determined by the UK's Building Regulations (Part L), or other benchmarks such as CIBSE's SLL Code for Lighting

(2012). The metrics to quantify lighting performance include illuminance values (in lux), Daylight Factor (DF) and Daylight Autonomy (DA) as percentages (discussed in Chapter 2). For specialised lighting requirements (e.g. museums, galleries) a Lighting specialist needs to be appointed. For simpler buildings, this is part of the responsibilities of the Sustainability Engineer.

- **What are the acoustic requirements for each activity?** Normally, the conditions of good acoustics are to minimise background noise, maximise wanted sound, and prevent echoes by achieving the appropriate Reverberation Times (RT) (Szokolay, 2008). The shape and size of the room, and the room surfaces' absorption and reflection properties affect this aspect. Certain rooms such as concert halls, theatres, and auditoriums require pertinent attention to this aspect. For these cases, a specialist Acoustician should be appointed. For simpler buildings, this is part of the responsibilities of the Sustainability Engineer.

- **Are there any pollutants that need special attention?** These include chemical pollutants in air and microbial pollutants in the water. The MEP Engineer is responsible to avoid sources of external pollution and recirculation of exhaust air as well as to minimise the risk of waterborne and airborne legionella. The Architect is responsible for minimising the emissions of Volatile Organic Compounds (VOCs), and other substances. Noise pollution also falls under this category; the need for noise attenuation from the environment should be examined carefully. At this point, an Interviewee (CS10/Architect) alluded the notion that this aspect is of high priority during RIBA stage 0.

- **What impact does the building have in the community?** The Landscape Architect, the Client, the Architect, and the Project Lead collaborate on softer issues that affect functionality, aesthetics, and social impact. Several Interviewees (CS1 / Architect / Sustainability Engineer, CS2 / Architect / Sustainability Consultant, and CS3/Architect) described the process of extensive engagement with building occupants and the community when designing education projects.

5.2.3.2. Environmental aspects

The "*Environmental impact*" category is concerned with the trade-off relationships between the building and the site. The following issues should be examined during briefing and concept design development (RIBA stages 1 and 2):

- **What are the site's location, topography and surroundings?** This aspect examines both the macro and microclimate of the site focusing on the climate and weather conditions. Therefore, climatic data include parameters such as the following: Location (latitude); Orientation (magnetic declination); Sun angle (clock time azimuth and altitude), Insolation (direct and diffuse solar radiation, W/m^2), Cloud cover (%); Temperature (average minimum, average maximum, Celsius); Rainfall/precipitation (mm per month); Relative humidity based on dew point (%); Wind analysis, speed (m/s), temperature (Celsius), direction and frequency each month or each season. The Sustainability Consultant, or Sustainability Engineer, should determine the above values by utilising a software package with climate analysis capability (e.g. IES-VE). Free software tools (e.g. Climate Consultant 5.5) are also available to perform this type of analysis. Data from weather stations can be downloaded by the U.S. Department of Energy web site as well as "*Climate.OneBuilding*" (2014-2016). Alternatively, specialised software tools (e.g. Meteonorm) combine weather data from different weather stations, for a specific site selected, offering more accuracy. Furthermore, an Interviewee (CS1/Architect/Sustainability Consultant) suggested that during site investigations they prioritise topography examination and material selection.

- **What materials are available in, or close, to the site?** The recommendation is to minimise the use of natural resources and embodied carbon/energy of materials (Hammond et al, 2011; Lazarus, 2004). Life-cycle analysis/assessment (LCA) examines the "*cradle-to-grave"* pollution caused by building materials. Materials that exist in the site, as well as recycled and responsibly sourced materials are the preferred options. The Architect and the Client collaborate to decide the selection of materials. Moreover, the Structural Engineer is responsible for the materials of the structural system; recycled aggregates should be considered to minimise waste.

- **What are the energy sources available at the site?** Energy sources for buildings usually are electricity, and fossil fuels. The metrics used to quantify their efficiency include the following: Primary Energy (PE), Delivered Energy (DE), and Useful Energy (UE). The most preferable sources of PE are from clean energy such as renewable energy sources (Zeiher, 1996): hydroelectricity, solar energy, wind energy, tidal and wave power, geothermal energy, and biomass. The MEP Engineer and the Architect are responsible for the selection of the energy sources. An Interviewee (CS5/ Architect/Sustainability Consultant) described the availability of clean energy and the reduction of energy use as the highest issue on the sustainability agenda.

- **What is the water availability at the site?** The most common sources of drinking water are surface water (e.g. streams, rivers, lakes, and reservoirs), underground water (e.g. springs and wells), and rainwater (e.g. roofs and paved surfaces). Rainwater availability and precipitation entail whether there is the possibility of implementing water-harvesting techniques. The Landscape Architect, MEP Engineer, Health Engineer, and Civil Engineer collaborate in cases where irrigation is needed.

- **What is the ecology at the site?** The minimum use of land has been recommended by the Interviewees. The Landscape Architect is responsible for minimising the building's footprint on the site. Strategies to enhance the ecology along with the long term impact of the building on biodiversity are examined by the Ecologist. These considerations include the re-use of land, and land contamination (BREEAM, 2014).

- **Is there risk of flood at the site?** The Landscape Engineer and the Civil Engineer collaborate to minimise the risk of flooding and to develop attenuation measures, where possible (HM Government, 2010). Sustainable Drainage Systems (SuDs) are also recommended (RIBA, 2013a; HM Government, 2010).

5.2.3.3. Client satisfaction and approval – commercial aspects

Commercial aspects respond to policy and regulatory compliance, also targeting to increase the marketability of the building asset. The questions that should be answered, by the project team, during briefing (RIBA stage 1) are the following:

- **What Level 2 BIM maturity standards are going to be used?** A number of standards have been developed so as to achieve compliance with the UK regulations (discussed in Chapter 3, Section 3.5.1). These include: BS1192:2007, PAS1192-2:2013, PAS1192-3:2014 for information management; BS1192-4:2014 for collaborative production of information; PAS 1192-5:2015 for security of information; BS8536:2015 for facilities management briefing, and Uniclass 2015 classification for organisation of information. The BIM Coordinator and/or the Information Manager are responsible for ensuring that the rest of the design team follows the selected standards (according to Interviewees CS7/BIM Coordinator, and CS8/ BIM Manager/BIM Coordinator).

- **What other standards will be chosen to guide the collaborative process?** The most commonly used framework is the RIBA Plan of Work 2013. Others include the Government Soft Landings (GSL), and the Digital Plan of Work (DPoW) BIM Toolkit (discussed in Chapters 2 and 3).

- **How are the contracts going to be set?** The CIC BIM Protocol, CIC Best Practice Guide, and CIC Outline Scope of Services (Construction Industry Council, 2013) establish obligations, and liabilities (discussed in Chapter 3). However, the definition provided by the CIC's BIM Protocol for sustainability deliverables is not only insufficient, containing a single row for "*sustainability analysis*", but also inaccurate. For concept design (stage 2) data drops, the sustainability analysis cells of the matrix are blocked, shown as grey, suggesting that sustainability analysis is not needed at this stage. Amendments to the existing contracts are needed, for SBD, in order to clearly acknowledge the responsibilities of project team's members towards sustainability. Furthermore, it has been suggested by the Interviewees that redistribution of payments needs to occur to accurately reflect contributions and cost savings due to the implementation of sustainable design strategies.

- **What are the requirements of the Building Regulations for sustainability?** The UK policies and regulations, for SBD, have been discussed in Chapter 3 (Section 3.5.1). These include the following: Part A (structure), Part B (fire safety), Part C (site preparation), Part D (toxic substances), Part E (noise attenuation), Part F (ventilation), Part G (sanitation), Part H (drainage), Part J (appliances), Part K (collision), Part L (fuel and energy), Part M (building access), Part N (glazing), Part P (electrical safety), Part Q (security). Local regulations and drivers should also be investigated at this point in the design process. Other standards include: PAS2050:2011, BS EN ISO 14064:2012 and GHG Protocol for greenhouse gas emissions; and BS EN15643-1and2, BS EN 15804, BS EN15978, BS EN 16309 for environmental performance. Several Interviewees have discussed compliance with local/regional sustainability policies such as carbon reduction (Sustainability Consultant/BREEAM Assessor), renewable energy (CS2/Architect/Passivhaus Consultant) as well as local heritage (CS1Architect, CS2/Architect/Passivhaus Consultant, CS9/Architect), where applicable, are essential in order to receive the planning permission. The Energy Performance Certificate (EPC) is another major driver, because it favours the possibilities to increase the market value of the asset, according to an Architect.

- **What certification assessment schemes could be implemented?** The Interviewees have nominated BREEAM (BREEAM, 2014) as the main method for assessing the sustainability outcome of building design targeting for "*Excellent*" and "*Outstanding*" for a variety of types of residential and non-domestic developments. Passivhaus and LEED certifications are common as well. Others recommendations include CASBEE, BEAM Plus, and Green Star. The selection of assessment method should be considered at this stage so as to appoint the specialist subcontractor who will guide this process (e.g. BREEAM Assessor). There has been consensus, among practitioners, that BREEAM and EPC are the main requirements for certification. The importance of setting clear sustainability targets at briefing stage, is stated in the following excerpt:

“The big one really is BREEAM and what rating you want to get and then everyone knows what they are aiming to do. But, there are other things as well, such as EPC rating and a number of benchmarks, really, of what they want to achieve and that is probably the most important thing, I would say.” (CS10/Architect/Sustainability Consultant)

- **What is the budget allowance for the building?** CapEx (Capital Expenditure) and OpEx (Operational Expenditure) should be estimated at this point (RIBA stage 1). For Clients that intend to occupy the building, a lifecycle cost assessment has been recommended. For Clients that intend to market the building, CapEx assessment and compliance with the requirements of the Building Regulations is usually sufficient. An Interviewee (Project Manager) suggested that when it comes to the final decisions about which sustainability objectives to set, they always implement all the no cost measures, and then, most of the low cost ones. Finally, they assess the viability of the more expensive measures based on CapEx and OpEx. A “c*ost benefit analysis*” of the whole lifecycle cost of the facility/asset is performed at briefing stage. The Interviewee concluded that: “*the simpler buildings perform always best*”, suggesting that passive design strategies (decided during concept design) are the most cost effective. The following excerpt supports this argument:

  “It doesn't cost any more money to change the orientation of the building or to put the glass in the right place, or to rearrange spaces, but all of those things that we do, have no extra cost.” (CS13/Sustainability Director/Engineer)

Sinclair (2013) has argued that the cost of making changes to the design increases exponentially beyond RIBA stage 3 (Developed design), as the opportunity to make changes to the design decreases. Thus, it is more economical to make changes to the design at the early stages, up to concept (RIBA stage 2), according to the recommendations of the specialist subcontractors. It has been argued that sustainability specialists (e.g. BPA expert) need to be involved from the inception of the project (from RIBA stage 0 onwards), when they can affect the design decisions of the rest of the design team. The importance of communicating sustainability in a project brief has also been discussed in the literature (Mills and Glass, 2009).

5.2.4. Initial project brief – sustainability objectives and metrics

The design practitioners have emphasised that sustainability targets and benchmarks should be quantified from the beginning, before the design starts (at RIBA stage 1). Interviewees (CS1/Architect, CS2/Architect) discussed that informed Clients have been setting clear sustainability targets prior to concept design (RIBA stage 2).

In case the Employer's Information Requirements (EIR) are not delivered by the Client, by the end of RIBA stage 0, the Lead Designer and/or the Sustainability Lead is responsible for clarifying the expectations by being proactive. Clear sustainability benchmarks assist the design team's coordination and help to streamline the process in order to achieve sustainability goals. Several sustainability experts have stressed the importance of commonly agreed, clear targets by the end of briefing, RIBA stage 1 (CS8/BIM Manager, CS9/Architect, CS9/Sustainability Director, CS10/Architect). Another important aspect of briefing is also assessing the viability of the sustainability targets, and suggesting alternatives. Best practices do not take the Client's brief as a given; instead, they challenge it so as to inform the Client about areas that need improvement (CS6/Architect/Sustainability Consultant, Sustainability Engineer/BREEAM Assessor). It has been argued, by the Interviewees, that briefing and concept design (RIBA stages 1 and 2 respectively) are the most critical stages of the design process to make sustainability decisions.

For BIM-enabled SBD, the sustainability targets and benchmarks should be explicitly stated in the EIR, for the case of an informed Client. When the EIR are not provided by the Client, it is the Project Lead's and/or the Lead Designer's responsibility to form a BIM Execution Plan (BEP) that states the sustainability targets along with the implementation strategy. Furthermore, the BEP should be communicated with the rest of the design team so as to ensure that everyone is working towards a common target. Otherwise, the BEP is the answer of the Design Team to the EIR, adding more detail. The BEP is developed collaboratively among the appointed design team members. Sections of the BEP include but are not limited to (Sinclair, 2013): (i) description of the project; (ii) project directory; (iii) contractual tree; (iv) Design Responsibility Matrix (DRM) and information exchanges; (v) project programme; technology strategy (software, hardware, and training); (vi) communication strategy (meetings, types of meetings, queries, data exchanges, format, and transfer mechanisms); (vii) common standards; CAD/BIM manual (coordination strategy, standards, coordination, collaborative process, reviews and quality control); and (viii) change control procedures.

Section 5.2.3 has discussed the ways in which the Project Lead can identify the Clients' aspirations during RIBA stage 0 (Strategic definition). During briefing (RIBA stage 1), the design team's values are added to the Client's aspirations and become more detailed as the feasibility studies start (e.g. climate analysis, site analysis, cost assessment). The result of this process is setting specific benchmarks for sustainability as part of the Initial Project Brief (Sustainability Objectives). Interviewees (CS2/Architect, CS3/Architect) have stated that the BREEAM manual's benchmarks should be determined during briefing (RIBA stage 1).

The Interviewees said that sustainability aspirations are expressed in both extremes, from very detailed (usually commercial Clients) to very vague, and everything in between, depending on how informed the Client is. In the case of a vague Client's brief, it is the Lead Designer's/Project Lead's responsibility to clarify the expectations by consulting the Client and engaging the specialist subcontractors, who are appropriate to that particular case study, so as to ensure the feasibility of the Client's aspirations by setting clear targets from the beginning (before design starts). An Interviewee stressed the importance of a proactive approach to design, by consulting the Client about their options:

> *"We have to be proactive. If the client doesn't have any aspirations. For example, the lifecycle of materials, where the client might not have an understanding about the design life or any requirements. We would put a proposal to them. You can start to discuss how certain elements of the building would have an effect. You have to inform the client." (CS1/Architect)*

Another important issue that one Interviewee (CS10/Architect/Sustainability Consultant) supported, is setting clear benchmarks before design commences. Setting clear goals from the beginning can create the necessary alignment for the design team to work collaboratively. The following excerpt illustrates this view:

> *"…if you don't have a benchmark, everyone is not working to a target, they are just working to a moving target, and it could move at any point." (*CS10/Architect/Sustainability Consultant)

An Interviewee (Project Manager) suggested that "*the simpler buildings perform always best*" discussing about passive sustainability strategies (e.g. optimised orientation, building massing, thermal mass use) that have been found more reliable in comparison to the complex building system strategies (e.g. innovative services and controls). These considerations suggest the implementation of a holistic view regarding materials, daylighting, ventilation with mechanical assistance (hybrid systems), based on the occupancy schedules of the building.

Another Interviewee (Sustainability Engineer/BREEAM Assessor) noted that cost is the bottom line objective for most Clients. Whereas another Interviewee (Sustainability Director) discussed that, the cost constraint does not affect the implementation of passive design strategies, which have a significant effect on the environmental performance of a building. This happens because decisions such as location on the building on site and orientation do not usually have any effect on cost, whereas their effect on building performance may be significant. The following comment emphasises this view:

> *"We sometimes focus on the cost and provide different strategies at different cost implication. But it's all with the best one, the cost." (Sustainability Engineer/BREEAM Assessor)*

An Interviewee (CS2/Architect/Sustainability Consultant) presented his definition regarding a holistic approach to sustainability goals in an A3 page that he described as "*my decision making tree*". The designer's sustainability priorities were presented as the main categories of a mind-map, and then, they were broken down into their subcategories accordingly. The distinct sustainability categories presented were the following: (i) BREEAM, (ii) Passivhaus, (iii) Overheating, (iv) Construction Design Management, (v) Client approval, (vi) Function, (vii) Insurance, (viii) Building regulations, (ix) Planning and Heritage, (x) Lifecycle Cost, (xi) Local Sourcing, and (xii) Embodied Carbon. Whereas not all of the above criteria are traditionally considered as directly linked to sustainability, these aspects are integral parts of the holistic SBD process. Another Interviewee (CS4/Architect) also talked extensively about efficiency and functionality of the architectural design, as well as planning and heritage considerations.

The benchmarks that the Interviewees have prioritised during briefing have been summarised in Chapter 4 (see Table 4.2) for each case study. The findings show that the experts prioritise maximising natural daylighting and ventilation, minimising embodied carbon of materials and energy use. These objectives are realised by utilising passive design strategies during concept design (RIBA stage 2). The findings support the idea that the early stage is the most critical time to make decisions for SBD.

By the end of briefing (RIBA stage 1), definite targets should be set for the sustainability aspirations, as described in Section 5.2.3. Briefing stage is the time to quantify sustainability aspirations so as to reflect specific metrics and benchmarks. For example, an Interviewee (CS5/Architect/Sustainability Consultant) described the benchmarks set for energy consumption; whilst the minimum requirement, by the Building Regulations, was compliance with Part L (2013), the Project Team decided to pursue compliance with Part L 2016 instructions for heating and hot water, electrical load, IT and small power, and carbon emissions, and thus, achieving a 40% uplift. Another Interviewee (CS3/Architect/Sustainability Consultant) described that during the briefing stage of CS1, initial Passivhaus pre-assessment took place based on developed schemes for the potential building. The following example reveals that the targets stated in the brief should be tested and not taken for granted. Another Interviewee (CS3/Architect/Sustainability Consultant) discussed that the unrealistic indoor temperature range requested by the Client, resulted in failing to achieve the energy consumption targets. A knowledgeable Sustainability Consultant should assess the knock-on effects of the set targets, and advice the Client accordingly.

5.3. Tasks and implementation methods

This Section discusses the opportunities, challenges, and limitations for the implementation of BIM-enabled SBD tasks utilising the existing technological enablers (discussed in Chapter 3, Section 3.5.2).

5.3.1. Schedule of services

Tables 5.2, 5.3, and 5.4 show the contribution of a wide range of core roles and specialists during Strategic Definition (RIBA stage 0), Preparation and Briefing (RIBA stage 1), and Concept Design (RIBA stage 2). The developed Schedule of Services, as an outcome of this research, define the roles needed for SBD in a clear way, which is something that has been missing from the literature. As discussed in Chapter 3, the sustainability roles and responsibilities have not been sufficiently defined in existing publications such as the CIC Scope of Services (CIC, 2007), RIBA plan of Work 2013 (RIBA, 2013a; RIBA, 2013b), "*Building Services Job Book*" (BSRIA, 2009), and "*Assembling a Collaborative Project Team*" (Sinclair, 2013). This is a critical gap because in order for the SBD process to be successful, all the components of the system need to perform at their best.

The ad hoc processes that are currently followed, for organising SBD, result in failing to deliver the correct sustainability information at the right time, and thus, lead to uncertainty to achieve sustainability goals. Accountability for succeeding, or failing, to achieve sustainability should be shared among the design team members according to their responsibilities. An Interviewee (Sustainability Consultant/BREEAM Assessor) argued that making responsibilities clear presents the biggest challenge for sustainability, as demonstrated below:

> *"During the design or after the design is completed, the BREEAM Assessor has to chase all stakeholders to get all the documents, all the evidence that are needed for the assessment. We have to go through everything and see what is relevant, and decide which targets are met, and which are not, and then, chase everyone again, and again, until you get all the correct documents." (Sustainability Consultant/BREEAM Assessor)*

Another Interviewee (CS5/Architect/Sustainability Consultant) supported the notion that the lack of engagement is caused by the reluctance of stakeholders to undertake responsibility to recommend the implementation of sustainability features in the building. Therefore, selecting the team members that share the same values, without worrying about liability, is important, as presented by the following excerpt:

> *"a lot of, a kind of, process in the discussion around BIM, how it informs design, is all about software. But actually the most important bit of it that we find in any ways, is the working relationship, is the personality side of it. So, you have to get people to get into it, into an open dialog without worrying about liability so much throughout the design process. So, rather than sat there and be terrified that you're gonna be blamed for something, you have to actually engage with the design at the early stage, and develop it all through" (CS5/Architect/Sustainability Consultant)*

Recognising the importance of each design role's contribution to achieve sustainability should also be reflected into the legal documents, and compensated accordingly. This is considered one way to address the occasional lack of engagement towards sustainability. As discussed in the previous sub-Section, the CIC's BIM Protocol (Construction Industry Council, 2013) "*Model Production and Delivery*", which is the most commonly used contract, is generic containing a single row for "*sustainability analysis*". Therefore, the shared responsibilities towards sustainability need to be acknowledged in a clearer way. Furthermore, for concept design stage, "*sustainability analysis*" and "*thermal simulation*" cells of the matrix are blocked, shown as grey, suggesting that sustainability analysis and assessment are not needed at this stage, despite the fact that this is the most critical time to make decisions regarding SBD.

Redistribution of payments have been recommended due to the changes that the BIM collaborative processes cause, as highlighted in the following statement:

> *"You should be starting at the beginning, and then, the building toward you designed. But the problem is the procurement route of the project doesn't pay enough money upfront to do that level at an early stage. The savings are going*

to come down the line, so redistribution of the fee structure to pay architects a bit more, pay engineers and structural and services people a bit more, and where you make the savings, in my view, it would be pretty all in there… You've shown that it works in 3D and you're saving the money downstream. But you need to put a little more money upstream to make sure it does work." (CS9/Sustainability Director)

An Interviewee (CS6/Architect/Sustainability Consultant) argued that the MEP Engineer, who also played the role of the Sustainability Engineer in this case study (CS6), needs to be better established and compensated for their contribution. The following excerpt remarks on the importance of this issue:

"It's understanding the value of that discipline that gets hammered at the early stages of design, which is probably key to getting it right. Most of the time, people would be quite happy to have an MEP consultant doing an energy strategy statement of broad line, but the broad strategy at early stage, and get them to do pipes and wires drawings during construction… and that's not already adequate any more, it needs to be a more of an engaged holistic design process." (CS6/Architect/Sustainability Consultant)

Table 5.2 Stage 0 (Strategic Definition) - Tasks to be undertaken

Stage 0 - Strategic Definition	
Project Roles	***Tasks to be undertaken***
All roles	☐ Perform site investigation
	☐ Contribute to the development of the Strategic Brief and EIR
Client/Client Adviser	☐ Provide Business Case
	☐ Select building site
	☐ Investigate user's needs
	☐ Appoint Project Team members
	☐ Determine budget allowance
	☐ Secure access to the site
Project Lead	☐ Develop Strategic Brief with Project Team
	☐ Assist in the Client develop the EIR
	☐ Discuss the appointments of design team members
	☐ Determine the BIM standards to be used
	☐ Develop Project Programme
	☐ Implement Integrated Sustainable Building Design
Lead Designer/Architect	☐ Explore material availability on the site
	☐ Explore daylight availability on the site
	☐ Overview of Building Regulations for Planning
MEP Engineer	☐ Determine community energy supply availability
	☐ Investigate the potential for renewable energy sources
	☐ Explore potential for natural ventilation
Structural Engineer	☐ Examine the potential of building re-use (façade, structure, recycled aggregates)
Civil Engineer	☐ Examine water availability
	☐ Determine the risk of flood
Cost Consultant	☐ Provide Cost Information
Sustainability Lead/ Consultant	☐ Discuss the Client's Sustainability Aspirations
	☐ Attain occupancy, site, and climate information
	☐ Explore the social and environmental context
	☐ Determine the Building Regulation's requirements for the type/s of activity/ies
	☐ Determine Certification Scheme to be implemented (e.g. BREEAM, Passivhaus)
	☐ Consult the Client regarding Sustainability Strategies

Table 5.3 Stage 1 (Preparation and Briefing) - Tasks to be undertaken

Stage 1 - Preparation and Brief		
Project Roles		**Tasks to be undertaken**
All roles	☐	Site investigation
	☐	Contribute to the development of the Initial Project Brief and BEP
Client/Client Adviser	☐	Consult with stakeholders
	☐	Examine possibility of shared facilities, and security
	☐	Examine proximity to amenities and public transport
	☐	Ensure maximum car parking efficiency
	☐	State the requirements for equipment for each designed space
Project Lead	☐	Develop Initial Project Brief, including sustainability targets
	☐	Prepare Contractual Tree, Schedule of Services, and Design Responsibility Matrix
	☐	Develop Project Programme and Handover Strategy
	☐	Review project progress process
Lead Designer/Architect	☐	Undertake Feasibility Studies
	☐	Undergo extensive consultation with building occupants
	☐	Ensure about the requirements of the Building Regulations for Planning
	☐	Examine shared facilities, security of spaces
	☐	Suggest materials' specifications (responsible sourcing)
	☐	Examine re-use of materials and low carbon materials
	☐	Determine building fabric's performance insulation, infiltration)
	☐	Determine daylight target benchmarks for indoor spaces
Landscape Architect/Ecologist	☐	Consider measures to protect and enhance site's ecology
	☐	Examine re-use of land
	☐	Strategize for hard landscaping and boundary protection
MEP Engineer	☐	Undertake Feasibility Studies
	☐	Advice the Project Team regarding Building Regulations (e.g. Part L and EPC)
	☐	Determine energy supply availability
	☐	Explore potential for natural ventilation and free cooling; set targets for indoor air quality
	☐	Set targets (benchmarks) for reduction of CO_2 (carbon dioxide) emissions; building fabric performance and infiltration; water consumption; NOx (nitric oxide and nitrogen dioxide) emissions
	☐	Determine required values of internal and external lighting levels and thermal comfort levels for each design space
	☐	Investigate the potential for renewable energy sources

Renewable Energy Engineer	☐ Explore the potential of renewable sources of energy (e.g. hydroelectricity; solar; wind; tidal and wave; geothermal; biomass)
Structural Engineer	☐ Examine the potential of building re-use (façade, structure, recycled aggregates)
Civil Engineer	☐ Examine water availability
	☐ Determine the risk of flood
	☐ Develop irrigation systems' strategy, if appropriate
	☐ Consider water management strategies
Geotechnical Engineer/Geologist	☐ Examine re-use of land possibility
	☐ Determine land contamination levels
Cost Consultant	☐ Calculate CapEx (Capital Expenditure) and OpEx (Operational Expenditure) during Feasibility Studies
Contractor	☐ Develop site waste management strategy
	☐ Assess construction site impacts
Sustainability Lead/ Consultant	☐ Perform climate and site analysis
	☐ Determine sustainability benchmarks
	☐ Undertake Feasibility Studies (utilising rapid modelling techniques)
	☐ Suggest Sustainability Strategies (social and environmental impact)
	☐ Develop initial schemes for the potential building
	☐ Coordinate Project Team's sustainability outcomes
Sustainability Engineer	☐ Perform climate and site analysis (sun angle, insolation, temperature range, rainfall/precipitation, humidity, wind analysis)
	☐ Assess feasibility of potential building schemes
	☐ Perform preliminary modelling using thermal models, lighting analysis, and ventilation analysis using CFD (Computational Fluid Dynamics)
BREEAM/Passivhaus Assessor	☐ Determine the goal of the Certification (e.g. Excellent, Outstanding) and the targeted categories (e.g. energy, materials, health and wellbeing)
	☐ Perform BREEAM/Passivhaus pre-assessment to assess feasibility
	☐ Advice the Project Team regarding the BREEAM/Passivhaus routes
BIM Manager/Coordinator	☐ Develop BEP's BIM strategies (technology, communication, standards, CAD/BIM manual, and change control procedures)

Table 5.4 Stage 2 (Concept Design) - Tasks to be undertaken

Stage 2 - Concept Design	
Project Roles	**Tasks to be undertaken**
All roles	☐ Provide required information of BIM Execution Plan
	☐ Contribute to the development of the Final Project Brief
Client/Client Adviser	☐ Approve sustainable design strategies
	☐ Approve architectural, MEP, civil and structural design
	☐ Consider responsible sourcing materials
	☐ Sign-off Concept Design and Final Project Brief
Project Lead	☐ Review Project Programme's progress
	☐ Issue Final Project Brief
Lead Designer/Architect	☐ Develop Design Programme
	☐ Undertake Feasibility Studies
	☐ Optimise facades
	☐ Optimise layouts
	☐ Design solar control devices
	☐ Monitor design process
	☐ Prepare architectural design drawings and BIM model (LOD100, LOD200)
	☐ Liaise with planning authorities to ensure compliance
	☐ Assess building materials' specifications (sourcing, carbon footprint, re-use, insulation, toxicity)
	☐ Ensure maximum daylighting availability. Utilise solar control to avoid overheating and glare.
	☐ Design outdoor space and boundary protection.
Landscape Architect/Ecologist	☐ Design hard landscaping and boundary protection
	☐ Design outdoor space. Consider enhancing site ecology
MEP Engineer	☐ Design MEP drawings and BIM model (LOD100, LOD200)
	☐ Develop artificial lighting strategy
	☐ Size water services and assess consumption
	☐ Advice the Project Team regarding Building Regulations (e.g. Part L and EPC)
	☐ Determine energy supply, and configure mechanical systems
	☐ Design for reduction of CO_2 (carbon dioxide) emissions; building fabric performance and infiltration; water consumption; NOx (nitric oxide and nitrogen dioxide) emissions
	☐ Design artificial lighting's zones and controls
	☐ Size HVAC services for each space to ensure thermal comfort. Examine free cooling strategies.
	☐ Configure cold and hot water supply

	☐ Assess building fabric's infiltration values
	☐ Ensure compliance with Part L, and EPC
Renewable Energy Engineer	☐ Review options of renewable supplies
	☐ Configure renewable sources systems
Structural Engineer	☐ Design structural drawings and BIM model (LOD100, LOD200)
	☐ Size structural elements
	☐ Consider thermal mass of structural materials
	☐ Assess embodied carbon of structural materials
	☐ Examine the potential of building re-use (façade, structure, recycled aggregates)
Civil Engineer	☐ Design Civil Eng. drawings and BIM model (LOD100, LOD200)
	☐ Design irrigation systems, water paths, and hard landscapping
	☐ Mitigate the risk of flood
	☐ Develop irrigation systems' strategy, if appropriate
	☐ Determine water supply
	☐ Implement water management strategies. Consider Sustainable Drainage System (SuDs).
Geotechnical Engineer/Geologist	☐ Mitigate land contamination levels
	☐ Ensure the re-use of land, if possible
Cost Consultant	☐ Calculate CapEx (Capital Expenditure) and OpEx (Operational Expenditure) during Feasibility Studies
	☐ Assess life-cycle cost's preliminary estimated value
Contractor	☐ Develop site waste management strategy
	☐ Prepare Construction Strategy
	☐ Assess construction site impacts
Sustainability Lead/ Consultant	☐ Perform climate analysis
	☐ Consult Project Team members regarding Sustainability Strategies
	☐ Review process to achieve sustainability benchmarks
	☐ Undertake Feasibility Studies (utilising rapid modelling techniques)
	☐ Coordinate Project Team's sustainability outcomes/strategies
	☐ Provide advice regarding material specifications, saving water and energy (social and environmental impact)
	☐ Test robustness to climate change
Sustainability Engineer	☐ Perform overshadowing analysis to determine the areas shadowed by the surroundings and the areas shadowed by the building. Consider "*Rights to Light*" regulation.
	☐ Perform solar radiation analysis
	☐ Perform detailed thermal modelling to assess the building's heating and cooling loads

	☐ Identify overheated areas of the building and consider localised solutions
	☐ Perform detailed daylight analysis simulations to determine natural lighting levels
	☐ Perform detailed CFD (Computational fluid dynamics) analysis to develop natural ventilation strategies (wind and airflow studies)
	☐ Calculate the embodied and lifecycle carbon of materials
	☐ Optimise the building's orientation to minimise energy consumption
	☐ Optimise solar control
	☐ Assess embodied carbon of building materials
	☐ Test robustness to climate change
BREEAM/Passivhaus Assessor	☐ Perform BREEAM pre-assessment based on feasibility studies
	☐ Advice the Project Team regarding the BREEAM/Passivhaus routes
	☐ Coordinate Project Team members to provide evidence to achieve credits (e.g. for BREEAM accreditation)
	☐ Assess the evidence provided by the design team
	☐ Perform design stage pre-assessment based on concept design drawings
BIM Manager/Coordinator	☐ Assist the team with software selection and interoperability
	☐ Determine information exchanges and validate information delivered
	☐ Coordinate BIM models and information (4D, 5D)
	☐ Detect, and report clashes. Resolve areas of uncertainty.
	☐ Prepare the architectural model before sharing for performance analysis
	☐ Coordinate with supply chain
	☐ Overview that the BEP is followed as planned
Acoustician	☐ Mitigate unwanted outside noises
	☐ Assess inside acoustic performance of spaces
Public Health Consultant	☐ Develop Health and Safety Strategy
	☐ Examine watercourse pollution possibility
	☐ Advice regarding flood risk and water recycling

5.3.2. BIM software use

The selection of BIM software tools varies according to the type of project. Large organisations utilise a variety of software packages so as to combine the strengths of different tools. For Phases 1 and 2 of data collection, twenty Interviewees out of twenty-five (20/25) were using the Revit suite for designing. Other tools used were ArchiCAD (2/25), Microstation (2/25), CATIA (1/25), and AECOsim (1/25). According to another Interviewee (Sustainability Director), the selection of BIM software tools differs depending on the type of project that is designed. For buildings, Revit and AutoCAD are the most commonly used software packages. Another Interviewee (CS9/Architect) argued that despite having used BIM software extensively, they have found that it was impractical for small projects. The reason for this notion is the investment in time and effort required for BIM. For larger projects, however, better support for BIM maturity and compliance has been reported; in that case, the Interviewee thought that it would be beneficial to use it "*only when it becomes affordable for smaller projects*". Four out of twenty-five (4/25) Interviewees discussed that they were not utilising BIM software. However, the first set of interviews was performed in 2013, as part of the exploratory stage of the research. This fact has also revealed that BIM software has become more widespread during the course of the research period (2013-2016). The findings suggest that a wide range of software tools is used depending on the type of project and design stage. The Interviewees (Sustainability Director and MEP Engineer/BREEAM Assessor) stated that they utilised Revit software for buildings, while they preferred Microstation software for infrastructure projects. For scheme design development (RIBA stages 1 and 2), SketchUp and Rhino were utilised instead due to their simplicity. Nevertheless, an Interviewee (CS6/Architect/Sustainability Consultant) described utilising Revit for performing feasibility studies during stage 1.

More importantly, the Interviewees stressed that BIM is more about the "*information tree*" process and less about the software tools, as reported below:

> *"... it is almost as a little tree of decision making... so rather than getting information out at one stage, you need broad scale of thinking at one stage,*

and then, slightly more detail, and then, slightly more detail again. So you get to the full detail again for performance. What you tend to do is get no information, no information, no information, and then, at the end, get full data sheet, full information, full performance, full modelling, full testing. At that point its kindda too late." (Architect/Sustainability Consultant)

For coordination of the different disciplines' models (architectural, structural, and mechanical services), Navisworks and Solibri software tools were utilised. An Interviewee (CS7/BIM Coordinator) discussed that although they utilise Navisworks for coordination, "*... Solibri is more advanced*". The reason for utilising Navisworks was their competence, and prior experience with the software. Another Interviewee (CS8/BIM Manager) said that: "*The main thing is that all the information is contained in the BIM model."* First, they put the information of environmental analysis in the BIM model, and then, they validate the model in Solibri software. They also reported doing some early environmental analysis themselves (in Graphisoft's EcoDesigner), making sure that all the participants have the correct information in the correct area. Then, the model "*would go to someone that has a specific platform, like IES*", for BPA. Apart from validating information, Solibri is used for creating rules that simplify the design process.

5.3.3. BPA software use

A wide range of BPA tools were utilised depending on the sustainability criteria examined, and the stage of design at which analysis takes place. Architects argued the importance of having quick feedback at early stages of design, when the building form is developed. Tools like PHPP (2/25), Sefaira (2/25), and EcoDesigner (1/25) were used for this purpose. However, for signing-off concept design, detailed simulation is still needed, by a Sustainability Engineer, who utilises a software package that is accredited to perform simulations in accordance with the National Calculation Method (NCM) (BRE). For this purpose, the Interviewees nominated the following accredited software packages: IES-VE (5/25), DesignBuilder (1/25), Bentley Hevacomp (1/25), and TAS (1/25). Table 5.5 shows the Sustainability Objectives aligned with the software tools utilised by the experts to assess them. IES-VE has been found to be the most extensively used software due to its functionality for BPA (e.g. solar, energy/carbon, light, climate, airflow, HVAC, UK and Ireland regulations, LEED, cost, and safety). Furthermore, a variety of tools have been utilised for specialised purposes (e.g. photovoltaics, daylight, BREEAM) so as to validate the software's calculations, ensure feasibility of the selected design strategies, and reduce the risk of failure.

Overall, the criteria for selecting BPA software were the following: (i) speed of analysis (e.g. Revit plug-ins, Sefaira, PHPP), (ii) accuracy of analysis (e.g. PHPP, IES-VE), (iii) NCM accreditation (e.g. IES-VE, Hevacomp, EcoDesigner), (iv) breadth of capabilities (e.g. Sefaira, IES-VE), (v) interoperability (e.g. plug-in or open standards), and (vi) prior experience with the tools. The processing power of computers is another important consideration for the use of detailed dynamic performance modelling. Furthermore, the BIM Task Group has recommended that the Client should not be prescriptive regarding the analysis software used for Building Physics, Environmental, Acoustic, Daylight analysis, Fire, Planning (4D) and Cost (5D). On the other hand, the information requirements, and Levels of Definition (LOD), need to be defined to minimise risk (BiM, 2013).

Table 5.5 BIM and BPA software tools used during RIBA stages 1 and 2

Design Stages	*Sustainability Objectives*	*BIM And BPA Software Tools*
Climate and Weather	Daylight availability Solar access/intensity Wind direction/intensity Temperature range Rainfall Humidity	Ecotect Sefaira Autodesk Revit PHPP IES-VE EcoDesigner EDSL TAS Bentley Hevacomp TRNSYS Climate consultant
Massing and Orientation	Overshadowing Building height and footprint Irradiance over building's planes Thermal performance Daylight Ventilation	Ecotect Sefaira Autodesk Revit IES-VE EnergyPlus eQuest PHPP iSBEM

Design Stages	***Sustainability Objectives***	***BIM And BPA Software Tools***
Fabric	Embodied carbon of materials Toxicity of materials Recycled materials Glazing and shading Daylighting Insulation (U-Values) Airtightness (at 50 Pa) Ventilation and free cooling Overheating Acoustic performance	Autodesk Revit IES-VE Sefaira EnergyPlus PHPP DesignBuilder EcoDesigner EDSL TAS Bentley Hevacomp TRNSYS EnergyPlus Radiance, Daysim
Services	Energy consumption Heating, cooling, and hot water Electric load IT and small power consumption Carbon/CO_2 emissions Energy source Artificial lighting Water consumption	IES-VE Bentley Hevacomp Modelica Sefaira EnergyPlus Autodesk Revit DesignBuilder EcoDesigner EDSL TAS TRNSYS Biomass Scenario Model Wind and Energy Resource Assessment (SWERA) Solar Deployment System (SolarDS) Open Studio
Life Cycle Assessment (LCA)	Controls and metering Lifecycle cost Occupancy and user feedback Robustness to climate change Robustness of materials and assemblies Flexibility/adaptability Waste	Athena EcoCalculator SimaPro L Umberto SMART Waste openLCA Open Studio
Cost	Capital cost (CapEx) Operational cost (OpEx) Lifecycle cost	IES-VE Building Life-Cycle Cost (BLCC) B2W Estimate HCSS HeavyBid Open Studio Green Building Studio
Holistic	BREEAM pre-assessment	IES-VE TaP Tracker Plus

5.3.4. Software interoperability

A major enabler to achieve integration of BPA with BIM collaboration is interoperability. Review of the latest advancements in software interoperability shows significant changes in this area. The new version of Revit (2016) integrates the preliminary sustainability assessment capabilities of Ecotect software tool (later Vasari, before integrated with Revit). Autodesk Revit 2016 integrates (built-in) the functionalities of climate analysis, early energy modelling and energy analysis, wind analysis, lighting analysis, and solar analysis studies. Furthermore, plug-ins for parametric computational analysis (tool: Dynamo), wind analysis (tool: Flow), daylight and electric lighting analysis, whole building energy analysis, and solar analysis. The benefit of these features is the rapid performance analysis that can be utilised while designing. However, the accuracy of those tools was questioned by several Interviewees (CS2/Architect/Sustainability Consultant, CS3/Architect). Furthermore, some Interviewees argued that the PHPP software has proven to be more robust in its estimations. However, the Interviewees (CS1/Architect, CS2/Architect) reported manual transfer of information from Revit to PHPP.

Sefaira software is another rapid parametric analysis software that was nominated by the Interviewees (Architects). The benefits of its use include quick estimations for a wide range of analysis, while maintaining an accuracy of 5% error, according to the developers (CS10/Architect) due to the EnergyPlus engine that it utilises. Furthermore, Sefaira has developed plug-ins for both Revit and SketchUp to facilitate seamless workflows. By eliminating the need to export geometry, information loss is avoided and the analysis presents fewer errors. Graphisoft's EcoDesigner STAR is the environmental performance software developed for ARCHICAD 19 that complies with ANSI/ASHRAE Standard 140-2007 (2011). Moreover, EcoDesigner provides a wide range of exports such as PHPP, iSBEM, VIP-Energy, gbXML, and IFC. However, these software tools are not NCM approved (EPBD-NCM, 2014) and were only considered adequate for preliminary analysis of scheme design (preferably at Stages 1 and 2 of the RIBA Plan of Work).

Figure 5.3 illustrates the built-in and plug-in rapid performance analysis possible with Autodesk Revit 2016.

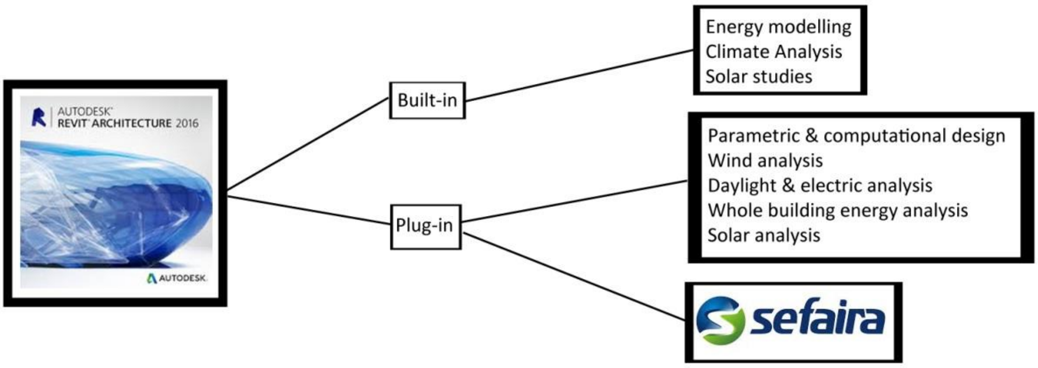


Figure 5.3 Revit 2016 rapid performance analysis capabilities

For more accurate, detailed and reliable analysis, which aligns with the Building Regulations (RIBA stage 2 onwards), the use of NCM approved software package is essential by a qualified specialist Sustainability Engineer and/or MEP Engineer. DesignBuilder (Design Builder Software Ltd.), IES-VE, Bentley Hevacomp, and TAS (Environmental Design Solution Ltd.) were the accredited software packages nominated by the Interviewees. IES-VE has also developed a plug-in for Revit (2008-2016) that works only if the same PC has licenses for both software tools. However, in most cases, the Architects, who utilise Revit and the Sustainability/MEP Engineers, who utilise IES-VE, belong to different organisations. As a result, the conversion into IFC or gbXML cannot be avoided. Bentley's Hevacomp has the capability of importing gbXML files for analysis, but the process was found to be smoother when utilising the corporate BIM software (AECOsim, Microstation).

Figure 5.4 illustrates the interoperability workflows between the BIM authoring tools and dynamic simulation software tools that are also NCM approved (UK Government, 2014). The geometric information and properties of the BIM models, if designed properly, can be seamlessly translated to be recognised by BPA software tools (EPBD-NCM, 2014). However, as it was reported by the participants, the opposite process is not possible at the moment. This fact remains a technological limitation that hinders the integration of sustainability information directly into BIM.

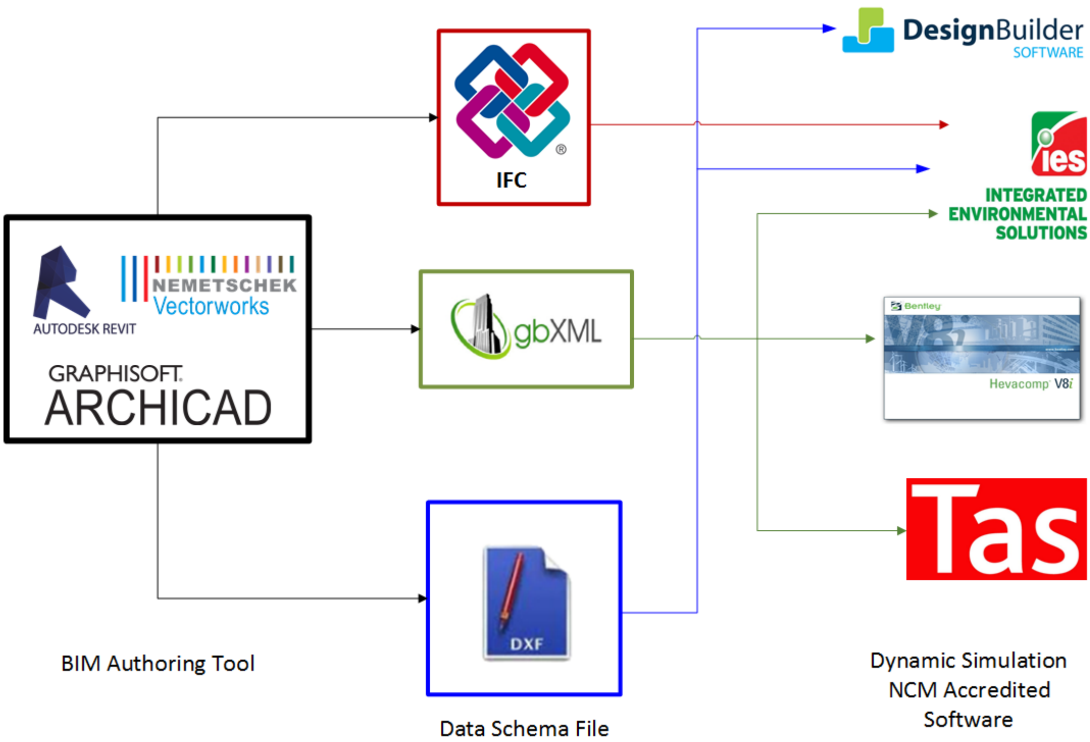


Figure 5.4 Interoperability between BIM authoring tools and dynamic simulation tools (NCM Accredited)

5.3.5. Utilisation of Common Data Environments (CDEs)

It was found that Sustainability Engineers were not utilising CDEs for collaboration. One Interviewee (CS9/Sustainability Engineer) emphasised that *"I am a sustainability specialist, I am not a specialist in BIM"*, arguing that sustainability is not relevant to BIM collaborative processes. This viewpoint reflects the current state of implementing SBD, and the lack of achieving nD modelling in practice. Furthermore, coordinating sustainability information that was required for BREEAM assessment was done manually, and was ad hoc. One Interviewee reported that *"sometimes we use the Tracker Plus system"*, but *"typically all things happen via email"* (BREEAM Assessor). As a result, BREEAM assessors spend a significant amount of time coordinating and validating the information provided by other project participants. The following comment describes the current state of practice for SBD implementation:

"It [BIM] has not affected the way I personally, manage sustainability… It is very important to embrace BIM, because there are some very good efficiencies to be achieved if everyone is on board, if the design team is on board, in a process of working together, using the same process." (Sustainability Consultant/BREEAM Assessor)

The findings indicate that the lack of clearly defined strategies for implementation of SBD, has hindered the use of ICT. During the second and third sets of data collection (2014 and 2015), the use of CDEs for exchanging information had become more common. The responsible party for setting the CDE was the Contractor, and a BEP was developed to coordinate the process. However, there was no account of sustainability considerations or deliverables, within the BEP. Nevertheless, the Architects were using a variety of cloud services such as BOX, Conject's BIW, 4Projects, Autodesk 360 Glue, TeamBinder, Asite's Adoddle, Dropbox, or private extranets.

An Interviewee (CS9/Architects) described that although no CDE was used, synchronous collaboration occurred utilising other types of ICT, such as telephone conferencing, while manipulating the model at the same time. However, meetings, phone calls, and emails remain the main forms of communication during SBD development. A significant technological limitation, stated by the participants, was that preparing the model to be shared with other disciplines, and uploading the BIM model, was a time consuming process that did not permit working on the cloud (CS6/Architect/Sustainability Consultant). Instead, the practitioners reported performing a cycle of transferring each design discipline's models once a week (CS2/Architect, CS6/Architect/Sustainability Consultant). Therefore, it was supported that the networks' and internet connections' capabilities may limit the use of ICT.

Another Interviewee (Sustainability Engineer/BREEAM Assessor) discussed the reasons for not preferring the CDEs for exchanging information. One reason reported was that the CDE changes at every single project, since it is arranged by the Contractor. As a result, designers are not accustomed to any particular CDE and the different login accounts and passwords were found difficult for them to manage. However, the most significant limitation was information retrieval; it was reported that the link, which leads to the information package, expired after a few days, and as a result, the practitioners were not able to download it when it was needed. Therefore, email remained the main form of communication: *"even if you send and upload a document on that software, you still have to send them an email and explain the stuff".* These issues could be addressed by adding functionalities to the CDEs that make them appropriate for SBD implementation and delivery of information.

Another Interviewee (Sustainability Consultant/BRREAM Assessor) claimed that the information managing systems, currently used, are not appropriate to coordinate the delivery of sustainability information because they are not designed for this purpose. Since there is no technological barrier, a clear process that is developed specifically for SBD would facilitate more efficient collaboration. An Interviewee (Sustainability Engineer/BREEAM Assessor) argued the need for a platform that integrates sustainability considerations within BIM-enabled collaborative processes, as shown below:

> *"I can see that being very valuable in the whole design process. But it's still something under development and the main people that are focusing on, or using this idea of, BIM are the Architects and the MEP engineers, and the Structural Engineers that need all their information together. There hasn't been a platform developed for sustainability just yet." (Sustainability Engineer/BREEAM Assessor)*

The findings have demonstrated that communication, for SBD, occurs mainly by utilising informal communication channels such as phone calls (for synchronous collaboration), and email (for asynchronous collaboration). Thus, the SBD collaborative processes remain ad hoc and invisible to the rest of the design team, since they are not recorded in the official system (the CDE). As a result, the SBD process becomes difficult to manage very early on, due to the large amount of information that is generated. Mapping the collaborative process of the best practices, and identifying their workflow patterns, can serve as a quality control mechanism for sustainability objectives. Furthermore, an audit trail can facilitate the transition from the spider-net communication diagram to a more centralised-hub solution. To achieve that, the informal information exchanges need to be understood, and clarified, so as to inform the formal system. The parts of the SBD process that need better definition are the meetings, queries, and data exchanges. Standardising the repeatable processes, for SBD, will enable the use of CDEs so as to translate the benefits of face-to-face communication for distributed teams, which are the norm in construction. The IDEF3 process model developed (in Chapter 6, Section 6.3) explores the possibility to map repeatable tasks, and milestones, so that their management can be automated in a CDE. The following two excerpts from the transcripts stress the importance of workflow management for the delivery of information during SBD implementation:

> *"… collecting emails, documents, and excels … it depends on how people file and store information, it lacks organisation. Most people don't have a clear process, and it can make it difficult when people swap process, or when someone takes a leave of absence for a certain time period" (CS14/Sustainability Consultant/BREEAM Assessor)*

> *"We are continuously working towards that goal now, of trying of having standard templates and standard ways of working … this means that always we are trying to improve compatibility, not least saving a lot of time." (CS4/Architect)*

The Interviewees supported the notion that face-to-face communication, assisted by BIM technology, is the most preferable way of collaboration. In the case of distributed teams though, the use ICT is the alternative that they would implement. The statement below reveals the fact that the designers prioritise face-to-face meetings to remote ones:

> *"I don't think that the collaborative environment can get around, or remove, the need to have very frequent meetings with all the design team and sketch. I don't think that you can remove that. We even find the tele-conferencing, if you've got a drawing in your hand, then you try and sketch and hold on to the video camera and share it, and I don't think anything beats sitting around the table and discussing it. You can have the models there, and you can view the models on screen and look at different options, but I don't think that we would look to*

try to remove that … there is one more important aspect that the other." (Architect)

5.4. Deliverables and information requirements

The findings indicate that despite acknowledging the capabilities of BIM software, there is consensus among the designers, that the SBD process is heavily driven by 2D drawings. In spite of working in Level 2 BIM maturity projects, the Interviewees reported that this fact had not affected collaboration with other disciplines in a way that is anticipated in theory. One Interviewee argued that *"whether you do it in 2D or 3D or if you do hand drawings; fundamentally that will be the same"* (Architect). Antithetically, a more streamlined process was documented (CS5/Architect), inserting climate data and sustainability targets into the geometric model before sharing it with the sustainability specialists for BPA. The Interviewee explained that utilising BIM software has simplified the process of information exchange with other design stakeholders. The narratives' descriptions are discussed in detail in Chapter 6 (Section 6.3).

5.4.1. Correspondence between project team members

Two types of correspondence have been identified in the implementation of collaborative SBD: (i) formal, and (ii) informal communication. The formal meetings align with the milestones at the end of each design stage (e.g. briefing, concept), and all the members of the Project team are involved. The Interviewees reported these meetings occurring anytime between every month, or every three months, depending on the size of the project. The meetings involve progress reports from every member of the Project Team, and Client approval is required. In the meantime, information exchanges include a cyclic upload of the BIM models, one each week, for the core disciplines (Architects, MEP Engineers, Civil Engineers), followed by a coordination exercise (CS3/Architect/Sustainability Consultant). For sustainability assessment, weekly meetings between the Architect and the Sustainability Engineer are the norm. A cyclic process of designing and assessing sustainability, is implemented: *"For each change, we had to come back and discuss the options, and then model them again"* (CS9/Sustainability Engineer). For this reason, design changes need to be controlled by a standardised protocol. However, daily communication consists of emails, phone calls, and face-to-face meetings. Thus, modelling the interactions between participants cannot be prescribed in a strict way due to the bespoke nature of each building project. One the other hand, the queries to make critical decisions during daily collaboration can be identified and defined. Identifying gateways and critical decision points, in the SBD process, can facilitate the Concurrent Engineering (CE) approach to SBD management.

For the BREEAM Assessor, the Sustainability Engineer/MEP Engineer is the most prominent collaborator, as discussed below:

> *"We, at least, arrange 3 meetings with them (the Project Team) throughout the process. And, if they have a professional MEP in the project, we arrange to meet them at least 3-4 times in person, or video conference meetings. But, we either email or call them most days, going back and forth with evidence, queries for questions, or assisting with anything. In more weekly basis, we will be interacting with them, or have a short meeting face to face; it could be 3 times, or it could be 6 or 8 times depending on the project." (Sustainability Consultant/BREEAM Assessor)*

> *"We are appointed through the building services engineers, who are largely involved in the project on other times, separate from us. If the design team is very keen on sustainability, we have 5-6-7 meetings at Stage C (Concept design)." (Sustainability Consultant)*

Moreover, the Interviewees (CS6/Architect/Sustainability Consultant) argued that the personality match between collaborators is the most important quality for collaboration that leads to the success of the project. The following excerpt supports this notion:

> *"The most important bit of it that we find, in any working relationship, is the personality side of it. So, you have to get people to get into it, into an open dialog without worrying about liability so much throughout the design process." (CS6/Architect/Sustainability Consultant)*

5.4.2. Data exchange format and file types

Several Interviewees (CS7/BIM Coordinator, CS8/BIM Manager, Sustainability Directors and Consultants) discussed about the importance of defining the contents and format of the BIM model, as well as clarifying who is responsible for which element so as to avoid duplication of elements. The BIM Manager (role), individual or team (who are usually members of the architectural team), is responsible for validating that the information contained in the delivered models is appropriate for the given purpose, in this case, for BPA. Therefore, for the SBD process to be functioning successfully, the BIM architectural model should be built having the BPA in mind (EPBD-NCM, 2014). A transparent SBD process can assist practitioners in understanding what the other disciplines need to perform their duties. However, duplicate work is hindering the SBD process; the Interviewees have reported having to reconstruct the model in IES-VE software in order to perform their analysis (Sustainability Engineer). It is argued that timely BPA is critical for the Architects to be able to make informed decisions so as to progress into more design detail. By reconstructing the model from scratch, the Sustainability Engineers were unable to provide feedback on the sustainability performance of the building timely, increasing the possibility of failing to achieve sustainability targets.

It was reported that the information exchanged consist of a mixture of 2D drawings and 3D BIM models (delivered by the Architects), and PDF reports including snapshots of the thermal model results explained (by the Sustainability Engineers). The Interviewees stressed that *“the process is no different than the traditional one, whatever the deliverables”* (CS9/Architect). The following sentence reflects this notion:

> *“BIM is nothing to do with software. It is about including information, not about a package.” (Sustainability Director)*

5.4.3. Defined design deliverables

Defining the file types is found not to be sufficient for achieving a seamless BIM workflow that is adequate for SBD. The deliverables need to be defined in a more specific way, indicating the elements that should be included in the model, along with the way that they need to be built. An Interviewee (CS3/Architect/Sustainability Consultant) stated that there is no technological barrier for interoperability between Revit (used by the Architects) and IES-VE software (used by the MEP Engineers/Sustainability Engineers) and the only problem that hinders the process is cultural. However, as discussed below, this is a false perception due to lack of communication, and proper coordination, between design team members:

> *"It is a cultural mind-set, a resistance to do it. There is no technological barrier to that. It is quite possible to do that. But... it is more willingness and interest into doing that." (CS3/Architect/Sustainability Consultant)*

On the other hand, Interviewees (Sustainability Engineers) explained that the BIM model, delivered from the architectural team, was not adequate for BPA. This is a process problem occurring due to lack of definition of deliverables, and the lack of an appropriate BEP for SBD. Miscommunication amongst the design team resulted in causing rework, and thus, delays in the project programme. The Sustainability Engineers reported that the way the entities were built in Revit (by the Architects), was not appropriate for performing simulations in IES-VE software. The following excerpts from the transcripts describe this problem in detail:

> *"It is possible to export an architectural BIM model directly into our simulations' software but we find it almost impossible to do that. That is hardly an issue with the software, but is also an issue with the process; the way that the architect works, they build the outside of the model, and the inside of the model, as a separate entities so the skin of the building the walls and windows will be built as one model, and the inside of the building as a second model. The two models are not related to each other so when you try to export it for use of analysis, the analysis model will fail. As the building develops, the same BIM tends to be used, which means that in no point in the process it could be exported. While, in theory BIM allows us to work in one model for environmental analysis, in practice that does work." (Sustainability Director/Engineer)*

> *"The problem is that the architects don't consider the purpose of the model for sustainable performance analysis. The model is too heavy and impossible to run*

in IES. A lot of interoperability issues, from the model that the architect develops and the software that you will be using. When I do thermal modelling, I want only basic geometry and the thermal zones correctly. IES cannot handle complex geometry; it cannot handle curves, you need to have no curves. You need to simplify the geometry to small planes, but not too many, or the software crashes. … The basic problem of IES is that it is too sensitive to geometry. You have to be very careful when building your model. It has issues with overlapping surfaces, for example, and if that happens the model does not run the simulation." (CS14/Sustainability Engineer and Consultant/BREEAM Assessor)

The following statement also reveals technological limitations of the software packages that create the need for more clarity within the BIM/CAD manual, in a way that it defines the components, which constitute the BIM model. By following standardised protocols for authoring BIM models, which are adequate for BPA, duplication of work can be avoided, and thus, sustainability assessment would require less time and effort. Therefore, streamlined BPA is possible, utilising the existing technological enablers, only if the SBD collaborative process is made clear before design starts. The excerpt below emphasises on this issue:

"If the model is built in a particular way, it can be exported. But the way it needs to be built, it does not recognise how architects work. The package expects them to build one room at a time, and put the furniture, the glass, and then, move on to the next room. What they do is work at a global scale, they design the outside of the building at once, and then, they design the inside separately. So, what they design, it doesn't work. How it can be solved is either by changing the workflow, if there is enough time allowed for the model to be constructed in that way, or it could be solved by improvements in the software that would recognise the building as built." (CS13/Sustainability Director/BREEAM Assessor)

According to the views of several Interviewees (Sustainability Engineers and BREEAM Assessors), the following changes could be implemented to improve the interoperability between BIM and BPA so as to tackle the above mentioned problems: (i) working within the same software to reduce processing time; (ii) specifying layers from the beginning; and (iii) specifying how the model would be sliced, and presented, broken down into floors and/or zones.

5.4.4. Level of Development (LOD) and Level of Information (LOI)

The definition of LODs as "*Level of development*" was published in the AIA E202 "*Building Information Modelling Protocol Exhibit*" in 2008 (AIA, 2008; AIA, 2014) and was updated in "*AIA G202-2013 Project Building Information Modelling Protocol*" (AIA, 2013). In the UK, the PAS 1192-2:2013 (BSI, 2013b) has defined the LOD as "*Levels of model detail*" for graphical content, and the LOI (Levels Of model Information) for non-graphical content. RIBA has also introduced the "*Level of design*" (LOD) in "*Assembling a Collaborative Project Team*" (Sinclair, 2013). During information exchanges between project team participants, the LOD and the LOI of the model are critical for achieving sustainability goals (Wu and Issa, 2014). However, the interviews revealed that the information exchanged was not adequate to serve the required purpose. A commonly defined standard could solve this problem.

Table 5.6 presents the research findings aligned with LODs. This comparison helps to establish the associations between the various definitions for LOD and the RIBA stages. More importantly, it suggests the information that is critical for BPA at each stage of design.

Table 5.6 LOD and LOI alignment for SBD

LOD (AIA, 2013)	***LOD (RIBA, 2013)***	***LOD (CIC, 2013)***	***RIBA Plan of Work 2013 Stage (RIBA, 2013)***	***Modelling Detail***	***Non-graphical information***	***Sustainability criteria***
LOD 100	Outline (Out)	1 - Brief	1 - Preparation and Brief	Site location; preliminary positioning; preliminary massing; layout (locate rooms and volumes)	Spatial requirements; performance standards (natural ventilation, temperature range); schedules; statutory requirements; user profiles; site conditions; critical surveys; environmental and ecological surveys; topography	Sustainability aspirations; overshadowing analysis; maximum building height; solar radiation studies; estimated energy consumption of scheme designs
LOD 200	Performance (P)	2 - Concept	2 - Concept Design	Geometry; dimensions; elevations; massing; size; form; volumes; orientation; master plan; glazing ratio for facades; shading depth and height; preliminary services specification	Preliminary material specification; target insulation values (U-Values) for walls, widows, roof, and ground floor; thermal mass; information on materials; preliminary code compliance; project scope; rules or thumb; individual early assessment; preliminary capital cost information	Embodied carbon and toxicity of materials; recycled materials; preliminary heating impact and overheating; estimation of heating and cooling loads; sensitivity analysis; preliminary life cycle carbon; preliminary life cycle cost; BREEAM pre-assessment; energy consumption; water consumption; air flows; CO_2 emissions; acoustic performance; Part L

LOD (AIA, 2013)	***LOD (RIBA, 2013)***	***LOD (CIC, 2013)***	***RIBA Plan of Work 2013 Stage (RIBA, 2013)***	***Modelling Detail***	***Non-graphical information***	***Sustainability criteria***
LOD 300	Performance (P)/ Full: Generic (F-G)	3 – Developed Design	3 - Developed Design	Definite window size/shape/location; materials; accurate location on site and orientation; accurate building envelopes; compact surface areas; accurate building services; numbering of elements, ceiling, voids; plant location and size; duct size	Estimation of quantities; energy source; controls and metering; artificial lighting; IT strategy	Energy consumption; heating, cooling and hot water; electrical load; IT and small power; CO_2 emissions; embodied carbon; complete BREEAM and (Display Energy Certificate) DEC estimation; water consumption; lifecycle cost
LOD 350	Full: Generic (F-G)	4 – Developed Design	3 - Developed Design	Detailed model	As above	Finale BREEAM estimation; finale DEC estimation; complete sustainability assessment and code compliance
LOD 400	Full: Proprietary (F-P)	4 - Production	4 - Technical Design	Construction details; daylighting and artificial lighting strategies and controls	Specification of dates; specification of products; definite contract; maintenance strategy	Air-tightness; handover strategy; commissioning and post-handover strategy; life cycle assessment, durability and cost
LOD 500	Full: Proprietary (F-P)	5 – Installation /6 – As constructed	5 - Construction/ 6 - Handover and Close	As-built validated model	Maintenance strategy	Post Occupancy Evaluation (POE); monitoring of actual building performance

5.5. Critical decision points and project programme

The identification of decision points is discussed in PAS1192:2-2013 (BSI, 2013b) as a critical aspect of the BIM process. Decision points in phase-gate review comprise two types of gates: (i) hard-gates when the design freezes until the review is conducted, and (ii) soft-gates that allow the project to proceed in parallel, thus enabling a CE approach to SBD. Hard-gates serve the purpose of committing to decisions collectively. For SBD, the hard-gates have been aligned with the end of each RIBA stage. Additionally, soft-gates have been identified throughout the SBD process (concept design) to define decisions that occur in parallel. The benefit of implementing soft phase-gate reviews is that the project is allowed to proceed in parallel with conducting the review. In order to achieve sustainability objectives, design strategies are implemented, and assessed, towards a set of criteria and benchmarks (see Chapter 7, Table 7.12). The timing when these decisions take place is crucial, since once commitments have been made early in the process, it is more costly to repeat the work that has already been done. To achieve that, the right information should be delivered to the right people at the right time. Identifying critical decision points also assists in determining the loops of an iterative design process. A mapped process that can be audited, along with soft-gates and hard-gates for SBD, would provide assurance that the sustainability objectives would be met. The critical decision points and information requirements, identified in this research, are discussed in Chapter 6 (Section 6.3) as part of the incidents' Narratives, and have been coordinated explicitly within the IDEF model presented in Chapter 7 (see Tables 7.12 and 7.10 respectively).

The sustainability criteria, metrics, and benchmarks that are used when making critical decisions, for SBD, should be defined before concept design starts, during briefing (RIBA stage 1). Thus, for BIM-enabled SBD, an explicit BEP for sustainability is essential. The following excerpt emphasises the importance of briefing for SBD:

> *"Fundamentally, if you are going to do sustainability and, I think, every architect does now to some extent, it HAS [emphasis] to happen from the beginning and that HAS [emphasis] to form a part of the brief, from the client,*

for the design team to work on. It is not something that you can tackle on the side, and particularly if you are doing things like BREEAM, it is something that you HAVE TO [emphasis] address from day one." (CS9/Architect)

An Interviewee (CS10/Architect) addressed a critical issue concerning the need for a new paradigm for project programmes. For BIM processes to be implemented successfully, the most time-demanding stage is at the beginning of design (CS6/Architect/Sustainability Consultant). Therefore it was suggested that the traditional project programmes should be re-examined to reflect this change. RIBA's "*Assembling a Collaborative Project Team*" (Sinclair, 2013) recommendations do not consider the fact that the BIM collaborative process is front-loaded (CS7/BIM Coordinator) (DeKay and Brown, 2014; Zeiher, 1996). Instead, the suggested "*Project Programmes*" do not allocate enough time for concept (RIBA stage 2), compared to the detailed design (RIBA stage 3). It is argued that the milestones of the SBD process need to be identified, and re-defined, for concept design, so that the project programmes align with the MacLeamy Curve (CURT, 2004). The following excerpts reveal a significant problem; design managers still underestimate the amount of work needed during concept design in order to achieve a sustainable building outcome:

"It's just about workflow and time scales, or lack of. That is difficult to make people understand. The allowance at the front of a job, the allowance of using BIM, is always at the back end, and all the effort is at the front end." (CS7/BIM Coordinator)

"There is a lot more work at the earlier stages and so… the bulk of the work, there is more of it earlier on, and then, less of it later on eventually. The difficult thing is that programmes haven't caught up with it. So, the programmes are traditional programmes but they don't reflect the amount of work in each of those stages. So, what happens is there is a huge demand at the start, 'cause the programme is very tight, and then, at the latest stages you have too much time to do it. ... It's the building programme. When someone is planning on from concept design, or briefing stage to completion, it's the periods of time it takes to do the different stages. The different RIBA Stages are shuffled differently. So the paradigm of the design stages needs to change as well." (CS10/Architect)

On the other hand, it has been reported that standardisation of templates resulted in significant time savings (CS4/Architect). Furthermore, more detailed definition for the Scope of Services can address the misunderstanding occurring during the weekly model updates. Defined tasks, deliverables, and timescales can assist the project team to realise the requirements of a front-loaded SBD process.

Another Interviewee (CS10/Architect) stated that the lack of a comprehensive CAD/BIM Manual has had significant effects on the Project's Programme, since it has resulted to duplication of work. The need to rebuild the thermal model, provided by the Sustainability Engineer, has caused time delays in the SBD process. As a result, the Architects progressed with design development without having the essential detailed BPA feedback. The implemented solution for this problem, was the use of rapid performance assessment software (e.g. Sefaira), which provided the Architect with quick BPA feedback during the early design stages.

5.6. Organisational maturity for SBD management

Although BIM adoption, in the UK, has increased in recent years (NBS, 2015b; NBS, 2016), the findings show that sustainability is still not considered as an integral part of the BIM collaborative process. While in theory nD modelling has been made possible by the technological advancements, it is not yet implemented in practice. As presented in the previous Sections, managerial and process issues have proven to be more significant than technological limitations as it has been found by Jung and Kang (2007). It has been argued that, for SBD, the problems discussed in Chapters 2 and 3 remain unsolved. Therefore, the biggest challenge for the efficient implementation of BIM-enabled collaborative SBD is the lack of coordination among people, tools, deliverables, and information.

This Section describes the existing strategic project management approaches for SBD implementation. The lack of a common definition for SBD, and the required information exchanges during its delivery, have resulted in uncertain outcomes and duplication of work. Due to the lack of common standards for SBD, it remains subject to interpretation, and ad hoc processes are followed. When working collaboratively, under a common process, the perspectives of the different disciplines are shared, and the outcome is enhanced. On the other hand, when each discipline works in isolated silos, the design outcome reflects conflicting views. The experts agreed that a common process, which is communicated among the design team, is needed for SBD to be successful. Thus, the definition of a multidisciplinary SBD process can assist practitioners to work collaboratively, and can add value to the design, by harnessing the talents of the various stakeholders.

5.6.1. Current planning approaches for SBD

Several Interviewees (Architects, Sustainability Engineers, and BIM Managers) described working in certified Level 2 BIM projects. Nevertheless, the SBD process was not integrated, occurred in parallel, and remained ad hoc. This research supports the notion that defining the EIR specifically for sustainability, at RIBA stage 0, is needed in order to achieve alignment of technical, managerial, and commercial aspects.

Despite the previous efforts to define SBD, confusion still exists regarding its requirements. This fact increases the risk of not achieving sustainability objectives. The Interviewees agreed that a defined process, that can be audited, can provide assurance that the sustainability goals are going to be met successfully (CS3/Architect/Sustainability Consultant, BREEAM Assessor). However, flexibility and adaptability is essential for this process, since most projects are currently bespoke (CS10/Architect). The responsibility-driven management approach offers this flexibility (Wirfs-Brock and McKean, 2003). Therefore, it is argued that a "*Consensus*" method (task-based and rule-based) can provide the guidance needed without restricting decision-making or creativity (see Section 2.3.3.1).

The Interviewees considered BIM as the way forward to facilitate SBD efficiently. Despite that fact, the data shows that the experts, who have been heavily involved in both BIM and SBD, practice them separately and sustainability is not integrated into collaborative processes, as defined by the current BIM standards. Currently, the implementation of SBD remains in Level 1 BIM maturity (see Figure 3.1 by Richards, 2010). This is mainly a process issue, due to the lack of definition of the SBD collaborative workflows. Consequently, BRE's BIM Level 2 Certificated Practitioner

Scheme (Building Research Establishment Ltd, 2015), which is currently utilised to prove BIM competence, does not consider sustainability as part of the design process. A clearly defined SBD process can assist to reap the benefits of the current technological enablers that facilitate centralised information for SBD.

5.6.2. The need for process standardisation

Although the development of a BEP has been established for projects utilising BIM, implementation of SBD remains separate, and is not amongst its considerations, according to the Interviewees (CS6/Architect, CS8/BIM Manager, CS10/Architect). In several cases, methods such as "*action lists*" (CS9/Sustainability Director), "*tracking schedules*" (CS6/Architect), and "*sustainability checklists*" (CS10/Architect) are utilised for organising SBD. In other cases, task allocation and sustainability implementation remain completely ad hoc (CS3/Architect/Sustainability Consultant, MEP Engineer, BREEAM Assessor). The need for a clear path, and a common paradigm, for SBD management, was argued by an Interviewee (Sustainability Engineer/BREEAM Assessor), as demonstrated below:

> *"I can see that being very valuable in the whole design process. But it's still something under development and the main people that are focusing on, or using this idea of, BIM are the architects and the MEP engineers and the structural engineers that need all their information together. There hasn't been a platform developed for sustainability just yet." (Sustainability Engineer/BREEAM Assessor)*

Another Interviewee (Sustainability Consultant/BREEAM Assessor) expressed the opinion that the information managing systems, which are currently used, are not appropriate to coordinate the delivery of SBD deliverables because they are not designed for this purpose. Thus, it was argued that a clear process, which is developed specifically for sustainability, is needed. Another Interviewee (Sustainability Engineer/BREEAM Assessor) discussed the need for a platform that integrates sustainability considerations within BIM collaborative processes. The following excerpt supports the idea that a holistic collaborative process, for SBD implementation, can significantly improve its practice:

"It (BIM) could greatly simplify certain bits of the process that are not perfect. That is quite a challenge to meet effectively, but there are some positive ideas out there, but I don't think it has changed the general workflow to involve sustainability. … It is very important to embrace BIM because there are some very good efficiencies to be achieved if everyone is on board, if the design team is on board, in a process of working together, using the same process." (Sustainability Consultant/BREEAM Assessor)

5.6.3. Attitudes towards design automation

Developing the IER and the BEP, for SBD, is demanding due the complexity of solutions and the iterative nature of design. The overwhelming amount of information generated from the early stages, makes SBD management difficult. It has been argued that, for SBD, the early stages are the most critical time to make decisions regarding the strategies and features of the building (such as fabric and orientation). For this reason, it is important to ensure that the appropriate sustainability considerations occur at the right time, and in an informed manner, before making commitments. Nevertheless, the lack of sustainability criteria within the BEP remains, despite the fact that certain aspects of the process are repeatable, and thus, they can be standardised to streamline SBD and reduce the risk of failure.

Furthermore, an Interviewee (Architect/Sustainability Consultant) discussed the need for flexibility and adaptability for the automation of the design process. While, other Interviewees (Architects, Sustainability Consultants) highlighted the need for guidance and advice, regarding sustainability considerations, also arguing that standard ways of working can "*save a lot of time*" during SBD. The following comment supports this argument:

"A useful tool that services engineers have is CIBSE Compass. I don't know any provision for architects so that you understand what you should do … and that would be useful not to necessary give the answers. To tell that you should be considering embodied carbon and the mass of your building right from the beginning of your project, for example. Just to stimulate the architect think, lead the process." (Architect/Sustainability Consultant)

5.6.4. Concurrent Engineering (CE) approach to SBD

The findings confirm that the SBD process is iterative and it is about assessing, revising, and re-assessing sustainability as design progresses (performing design-assessment loops). Several Interviewees (Architects, Sustainability Consultants and Engineers) described the ideal design process (best practice) as concurrent design development and assessment (discussed in Chapter 6 in detail). Certain Interviewees described this practice as an ad hoc process; the successful collaborative outcome had been a result of the established relationships and alliances between organisations. In most cases though, the Interviewees (Architects, Sustainability Consultants/Engineers, and BREEAM Assessors) reported that they failed to achieve sustainability goals due to the lack of a concurrent approach to design development.

The Interviewees have emphasised on the importance of "*an engaged holistic design process*" (CS6/Sustainability Consultant). The following excerpts reveal the attitudes of the experts towards a concurrent holistic approach to SBD:

> *"It is not a milestone, it is a continuous flow of information, backwards and forwards, every time someone makes modification. That information is updated and is mainly on people knowing when you are going to need the information." (Sustainability Director)*

> *"...it is almost as a little tree of decision making... so rather than getting information out at one stage, you need broad scale of thinking at one stage, and then, slightly more detail, and then, slightly more detail again. … What we are looking to do is fill that tree of information and that knowledge throughout the course of a project." (Architect/Sustainability Consultant)*

The CE approach to concept design development implies that the Work In Progress (WIP), as defined by BS1192:2007 (BSI, 2007), does not occur in isolated silos for each discipline. On the contrary, it is a vibrant stage when concept ideas are exchanged between different stakeholders so as to shape and define the final project brief. For Level 2 BIM maturity, the information exchanges, and critical decisions' points need to be defined. This research aims to develop a CE process model for concept design (RIBA stage 2) by utilising the IDEF3 notation (Mayer et al., 1995). This model spreads within the spaces of WIP and Shared folders of the CDE (see Chapter 3, Figure 3.2). The model will assist in facilitating a holistic approach for SBD management, as described in the excerpt below:

> *"It's a little bit alien to some engineering practices to actually do that, to receive fixed information to design from, and what we kind of say, that's not a sustainable working model in the current construction industry… everyone must engage at the start, and help build that design. Otherwise there will be left with problems that can't be solved because of the tightening in regulations, and the tightening in Part L and energy performance. You can't just design an old building anymore, and then, stick a bit of insulation and make it work. The whole thing is got to be modelled, and tested, as kind of holistic design process..." (CS6/Architect/Sustainability Consultant)*

5.7. Summary

This Chapter has defined the components that constitute the SBD process framework. First, the roles and responsibilities of the project team members have been presented (in Section 5.2). Then, the Schedule of Services along with the technological enablers to perform these tasks have been discussed (in Section 5.3). Section 5.4 has examined the deliverables and information exchanges' content and methods. Section 5.5 has argued the need for a front-loaded SBD process with defined decision points. Finally, Section 5.6 has explored the organisational maturity of current practices and their attitudes towards a structured process for SBD implementation.

The results of this Chapter indicate that process standardisation, design automation, and a CE approach can assist in facilitating SBD more efficiently than the current ad hoc collaboration workflows. More importantly, it has been established that such an approach is currently missing for SBD, although it is much needed to improve collaboration. The next Chapter identifies the patterns that occur during collaborative SBD so as to develop a structured process model for the early stages (RIBA stages 0, 1, and 2) based on lessons learnt (successes and failures) of the best practices.

Chapter 6

Development of SBD process model and system architecture

6.1. Introduction

The previous Chapter has presented the framework of components that constitute the BIM-enabled SBD process and discussed the need for its standardisation. This Chapter contains the development of the process model for BIM-enabled SBD collaboration. As described in Section 4.7 (in Chapter 4), the IDEF (Integrated DEFinition) process model decompositions have been developed through a series of inductive and deductive steps. Section 6.2 contains the high-level decompositions, which have been developed, and validated, during Phase 1 (exploratory stage). Then, Section 6.3 describes the coordination of the SBD components, and the development of detailed decompositions, based on incidents' narratives utilising the Critical Decision Method (CDM) (Klein et al., 1989) during Phase 2 (main data collection and analysis). It identifies the patterns that occur during collaborative design of sustainable buildings in order to develop a standardised model for the early stages of SBD based on lessons learnt (successes and failures) of the best practices. The complete process model (before the final validation and refinements) can be found in Appendix D. Then, Section 6.4 presents the development of a system's architecture for a workflow management tool for SBD process automation (Green BIM Box, GBB). Finally, Section 6.5 summarises the findings of this Chapter.

6.2. High-level IDEF0 process model [Stages 0 – 1 – 2]

During the first round of interviews (Phase 1, Exploratory stage), the participants confirmed the hard-gates of the IDEF0 model that was developed based on the RIBA Plan of Work 2013 (see Section 4.7.1). The complete process model utilises both the IDEF0 and IDEF3 notations, and aligns with RIBA's (2013) stages 0 (Strategic Definition), 1 (Preparation and Brief), and to 2 (Concept Design) (depicted in Figure

6.1). These stages correspond to the three stages of briefing; Strategic, Initial, and Final, respectively. The definition of sustainability is re-framed as the level of detail increases. Sustainability aspirations need to be expressed qualitatively at stage 0, then, quantified (e.g. metrics, benchmarks) at stage 1, and finally, tested and defined explicitly at stage 2. Feasibility of the criteria is the basis for optimising the design, by performing iterations at Concept Design stage. Therefore, it is important for design practitioners to ask the appropriate questions at each stage of the design process.

The IDEF0 model, shown in Figure 6.1, uses the ICOM (Input, Control, Output, and Mechanism) notation (Knowledge Based Systems Inc. (KBSI), 1993), as presented in Section 4.6.2. Each side of the function box has a standard meaning in terms of box-arrow relationships. Arrows entering the left side of the box are Inputs. Inputs are transformed, or consumed, by the function to produce outputs. Arrows entering the box on the top are Controls. Controls specify the conditions required for the function to produce correct Outputs. Arrows leaving a box on the right side are Outputs. Outputs are the data, or objects, produced by the function. Arrows connected to the bottom side of the box present Mechanisms; these are upward pointing arrows that identify some of the means that support the execution of the function. Moreover, other means may be inherited from the parent box. Furthermore, Mechanism arrows that point downward are Call-arrows. Call-arrows enable the sharing of detail between models (linking them together), or between portions of the same model.

The IDEF3 decompositions of the RIBA stages 0 and 1 can be found as part of the complete process model in Appendix D. In addition, the refined process model is discussed in detail in Chapter 7 (Sections 7.4.6 and 7.5). The following Section demonstrates the development of the detailed decompositions for RIBA stage 2 (Concept Design). The developed decompositions identify Model/BIM Uses (i.e. tools, processes, and tasks) and Model-based deliverables (i.e. outputs) (Succar et al., 2016) of BIM-enabled SBD.

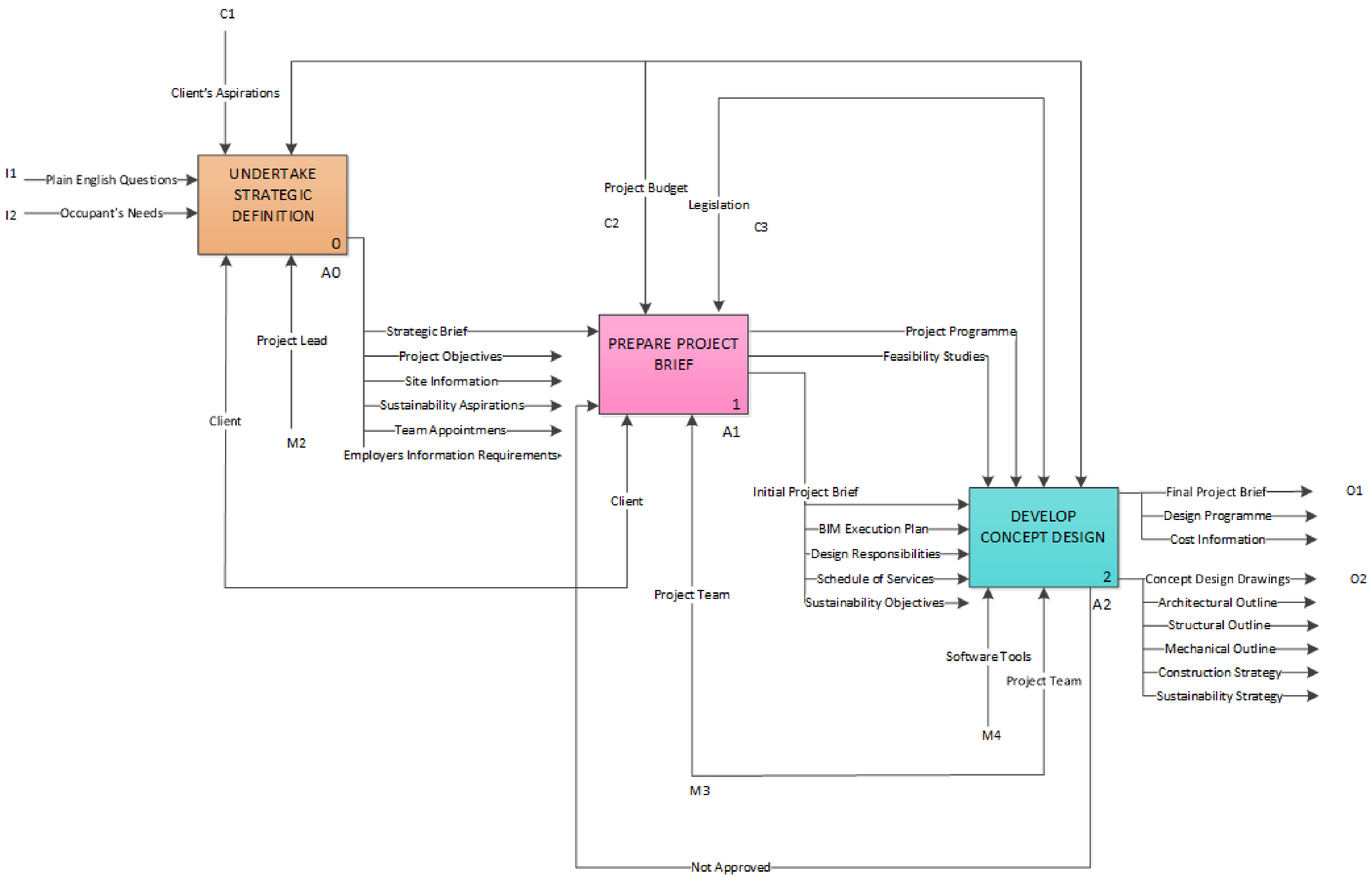


Figure 6.1 High-level IDEF0 decomposition diagram

6.3. Detailed IDEF3 process decompositions [Stage 2]

When developing an action plan for BIM, the six essential elements are: (i) the strategy, (ii) uses, (iii) process, (iv) information, (v) infrastructure, and (vi) personnel (CIC, 2011). This Section demonstrates the Model/BIM Uses (i.e. tasks delegated to design roles), Model-based deliverables (Succar et al., 2016), and information requirements, and coordinates them into a holistic process for SBD. The tasks, or Units of Behaviour (UOBs), that are included in the developed IDEF3 process model, are the BIM-enabled SBD uses, which are performed utilising BIM and BPA software, and a CDE. The following sub-Sections present the findings from the interviews utilising the CDM (Klein et al., 1989) to elicit the experts' knowledge so as to determine detailed-level IDEF3 processes and sub-processes (Mayer et al., 1995), for Concept Design (RIBA stage 2). The following Narratives (1 to 20) serve the purpose to validate, and enrich, the model by providing information from incidents based on the experts' experience. Thus, the patterns that have been identified to exist between the incidents' descriptions aim to increase the reliability of the process model. Figure 6.2 illustrates the hierarchical relationships of the UOBs' decompositions discussed in this Section.

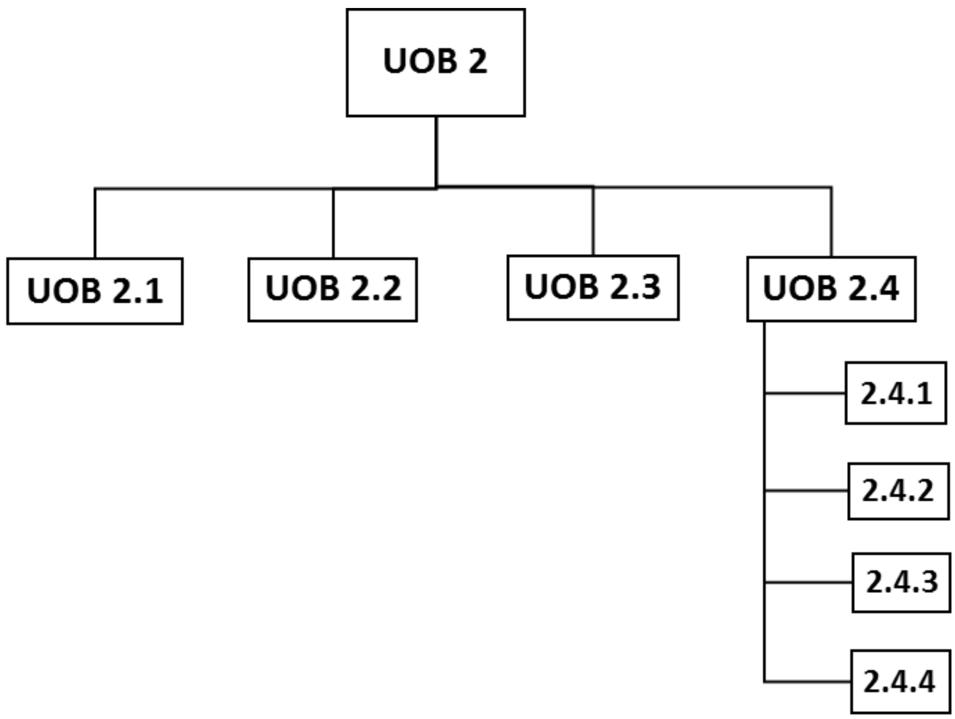


Figure 6.2 Hierarchical relationships of Stage 2 decompositions

IDEF3 (discussed in Section 4.6.2) uses the "*scenario*" as the basic organising structure for establishing the focus and boundary conditions for the process description. This is motivated by the fact that humans tend to describe what they know in terms of an ordered sequence of activities they have experienced, or observed, within the context of a given scenario or situation (Mayer, 1992). Moreover, IDEF3 is designed to provide a medium for capturing the raw description of facts known by domain experts about how their system works. Among its strengths is that it can combine many scenarios and viewpoints into a single diagram while also being tolerant of partial or inconsistent descriptions (ibid.). The following scenario Narratives (1 to 20) have served to identify the BIM-enabled SBD sub-processes' interdependencies, and the names of their functions. The IDEF3 decomposition diagram presents the sequencing and structure of the SBD process' workflows. As a result, the IDEF3 diagrams, developed in this research, illustrate the identified relationships between BIM-enabled SBD uses (as UOBs), the gateways and critical decision points (as Junctions), and the iterations' cycles of the SBD collaborative process. The Inputs (information required) and Outputs (information shared) of the functions are illustrated as Objects. The Objects' states (e.g. Initial, Optimised, Approved, Shared) change as they are altered by the functions. The UOBs that are added or amended by each of the Narratives, during the development of the model, have been coloured accordingly. The presentation of the Narratives is organised in a hierarchical manner, so that the high-level descriptions come first, and then, the detailed descriptions. Furthermore, the Model/BIM Uses and Model-based deliverables have also been validated, and enriched, by unstructured descriptions given by the Interviewees.

Figures 6.3 to 6.7 illustrate the evolution of each UOB's decomposition. The circles within the timelines have been colour-coded according to the colour of each Narrative's UOBs. The black-coloured circles correspond to Narratives that have validated the process model without suggesting any changes to its functions.

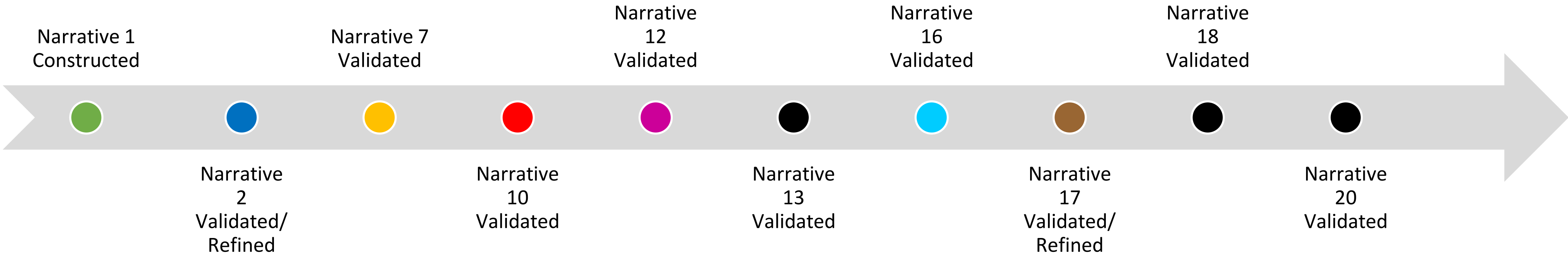


Figure 6.3 Evolution of UOB's 2 decomposition

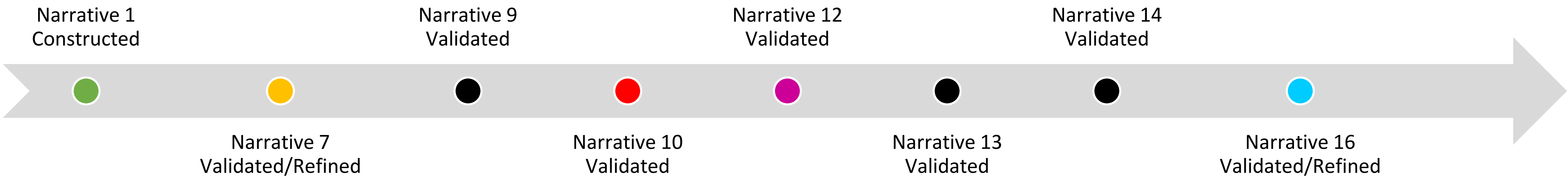


Figure 6.4 Evolution of UOB's 2.1 decomposition

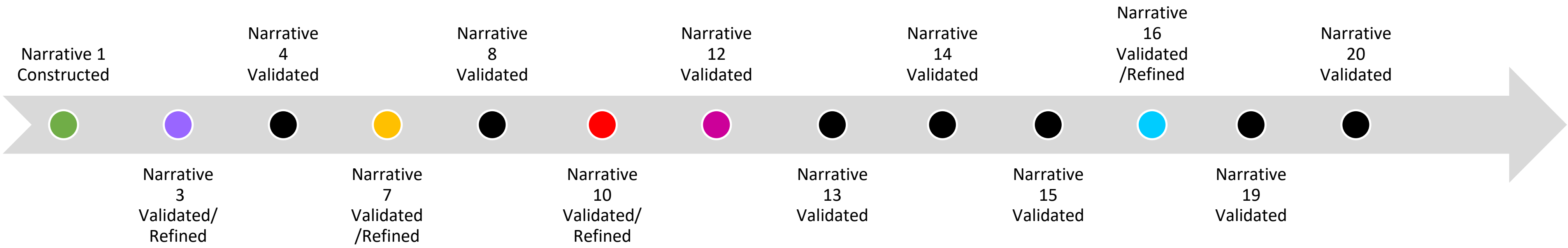


Figure 6.5 Evolution of UOB's 2.2 decomposition

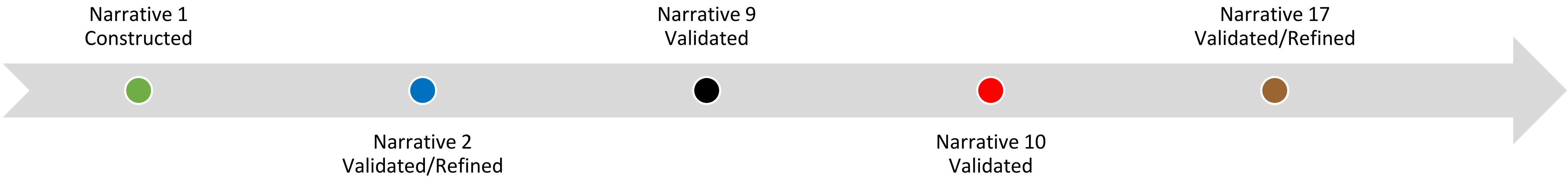


Figure 6.6 Evolution of UOB's 2.3 decomposition

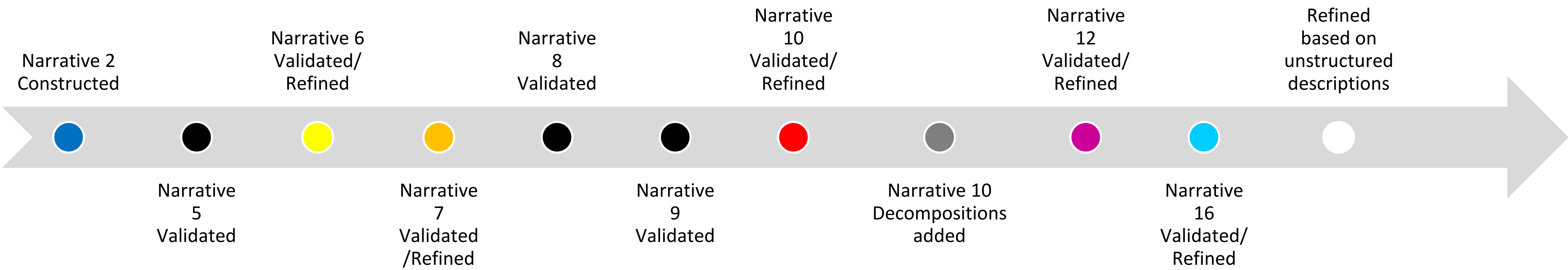


Figure 6.7 Evolution of UOB's 2.4 decompositions

6.3.1. Narrative 1: Concept stage's soft-gates/iterative loops [Green UOBs]

Once the requirements' definition phase is completed, at RIBA stage 1 (briefing), the climate data, occupancy requirements, and site and topography information are available. A Sustainability Engineer/BREEAM Assessor described a high-level process that is divided into four phases of design and assessment loops: (i) building massing; (ii) fabric and layout optimisation; (iii) mechanical systems configuration; and (iv) simultaneous optimisation of building envelope and mechanical services. Figure 6.8 illustrates the high-level decomposition diagram of stage 2, utilising the IDEF3 notation. UOBs 2.1, 2.2, and 2.3 correspond to the four assessment loops of SBD. Junction one (J1) represents the fourth phase, when mechanical services and envelope are optimised simultaneously. This process aligns with the three-part framework (i.e. site, envelope, and services) developed by Brown and Dekay (2000). Furthermore, it includes (aligns with) the BPA uses, for sensitivity analysis during performance optimisation, identified by Attia et al. (2013).

Figures 6.9, 6.10, and 6.11 present the detailed decomposition diagrams of UOBs 2.1, 2.2., and 2.3, respectively. During the requirements definition (briefing), the designer targets to find the comfort and climate mismatch for each season, and performs analysis to understand which passive design strategies are appropriate to mitigate the climate's impact examining parameters such as temperature ranges, solar availability, wind direction and intensity, and humidity. At Phase 1 (UOB 2.1) "*building massing*", an initial building mass is developed (UOB 2.1.1), by the Architect (LOD100 - Initial). Then, sensitivity studies are performed, by the Sustainability Engineer, in order to understand the heating and cooling loads (UOB 2.1.2) of each alteration of the building's form so as to reduce the energy consumption. Along with that, overshadowing studies are performed (UOB 2.1.3), in order to see how the building casts shadows on itself and on neighbouring buildings. The optimal orientation that reduces the heating and cooling loads is also examined (UOB 2.1.4). The result is the optimised Architectural BIM LOD100. During Phase 2 (UOB 2.2) "*fabric and layout optimisation",* the sizes, location of windows, location of rooms, types of façade (e.g. curtain walling), and U-Values of materials, are developed by the Architect (UOBs 2.2.1, 2.2.2, 2.2.3), while checking compliance with planning requirements. Then, the

Sustainability Engineer performs daylight analysis (UOB 2.2.4), and assesses natural ventilation (UOB 2.2.5), and heating and cooling loads (2.2.6). Then, Phase 3 (UOB 2.3) "*mechanical systems configuration*" starts. The MEP Engineer develops the energy strategy configuring the HVAC services, artificial lighting, and energy sources (e.g. renewable) so as to minimise CO_2 emissions while achieving the targeted comfort criteria (UOBs 2.3.1, 2.3.2, 2.3.3, 2.3.4), and improve efficiency. During Phase 4 (J1) "*simultaneous optimisation of building envelope and mechanical services*" a holistic approach is implemented, by examining different materials' performances (Architect), and assessing the environmental and thermal performance (Sustainability Engineer) (LOD200). Compliance with the Building Regulations (e.g. Planning, Part L, EPC) is assessed along with the sustainability criteria at each decision point (J1-J10). If the initial Planning Requirements are not met, the design needs to be revised accordingly. Junctions J1, J4, J8, and J10, have been identified as the critical decisions points of the BIM-enabled SBD process for concept stage (see Table 6.1). The following comment discusses the iterative loops, of design and assessment, which occur between the Architect and the Sustainability Engineer:

> *"We embed this information into our analysis, and then, feedback at what the output is, and if it's good or bad, they (the architects) have to revise their plans accordingly." (Sustainability Engineer/BREEAM Assessor).*

Table 6.1 Sustainability criteria of Narrative 1

Decision points	***Sustainability criteria***
J1	Overheating; Properties of materials (e.g. U-Values).
J4	Overshadowing; Building height; Heating/Cooling loads.
J8	Embodied carbon of materials; Toxicity of materials; Recycled materials; Glazing and shading; Daylighting; Insulation; Ventilation and free cooling; Heating/Cooling loads.
J10	Energy sources; Energy consumption; Carbon emissions; Artificial lighting; Water consumption.

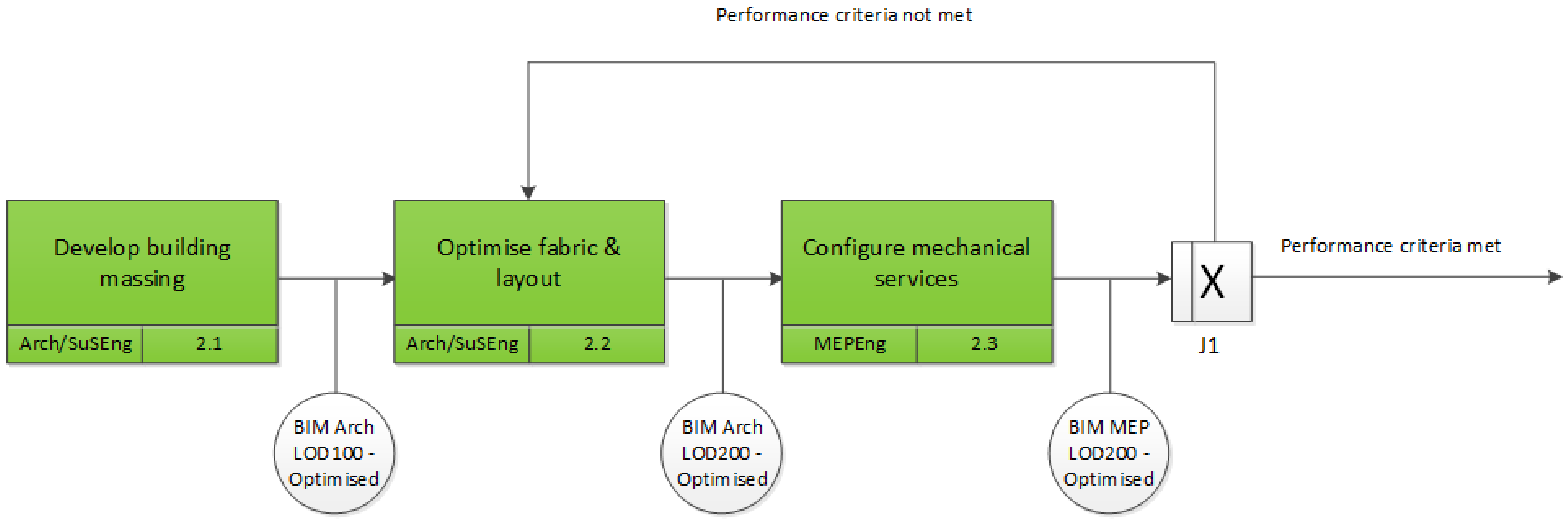


Figure 6.8 High-level decomposition IDEF3 diagram of Stage 2 "Develop Concept design" [Green UOBs]

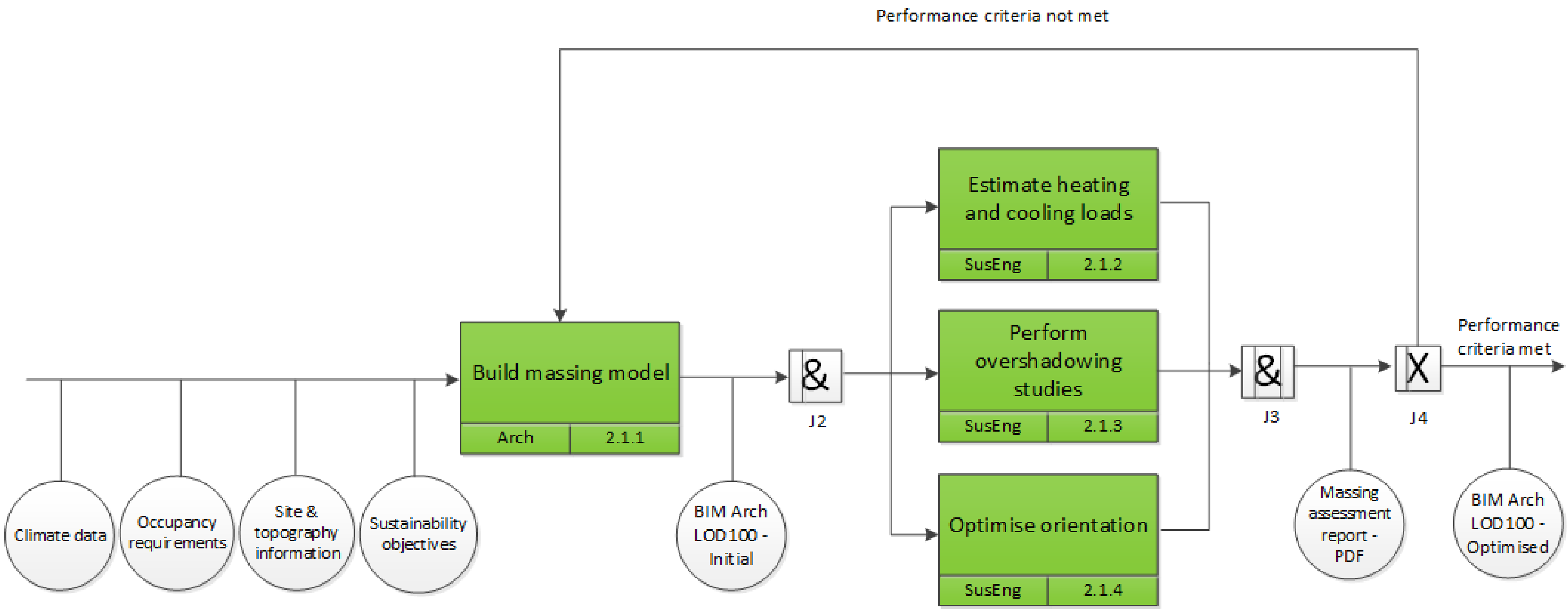


Figure 6.9 Decomposition of UOB 2.1 "Develop building massing" [Green UOBs]

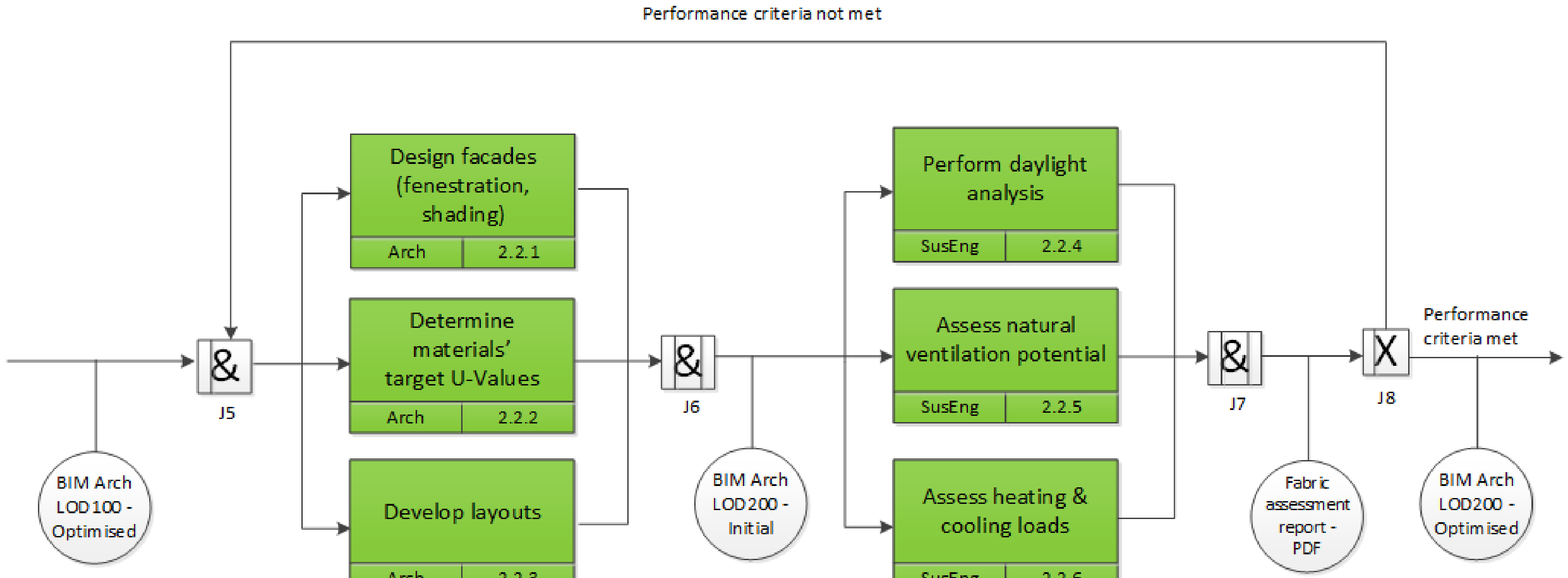


Figure 6.10 Decomposition of UOB 2.2 "Optimise fabric and layout" [Green UOBs]

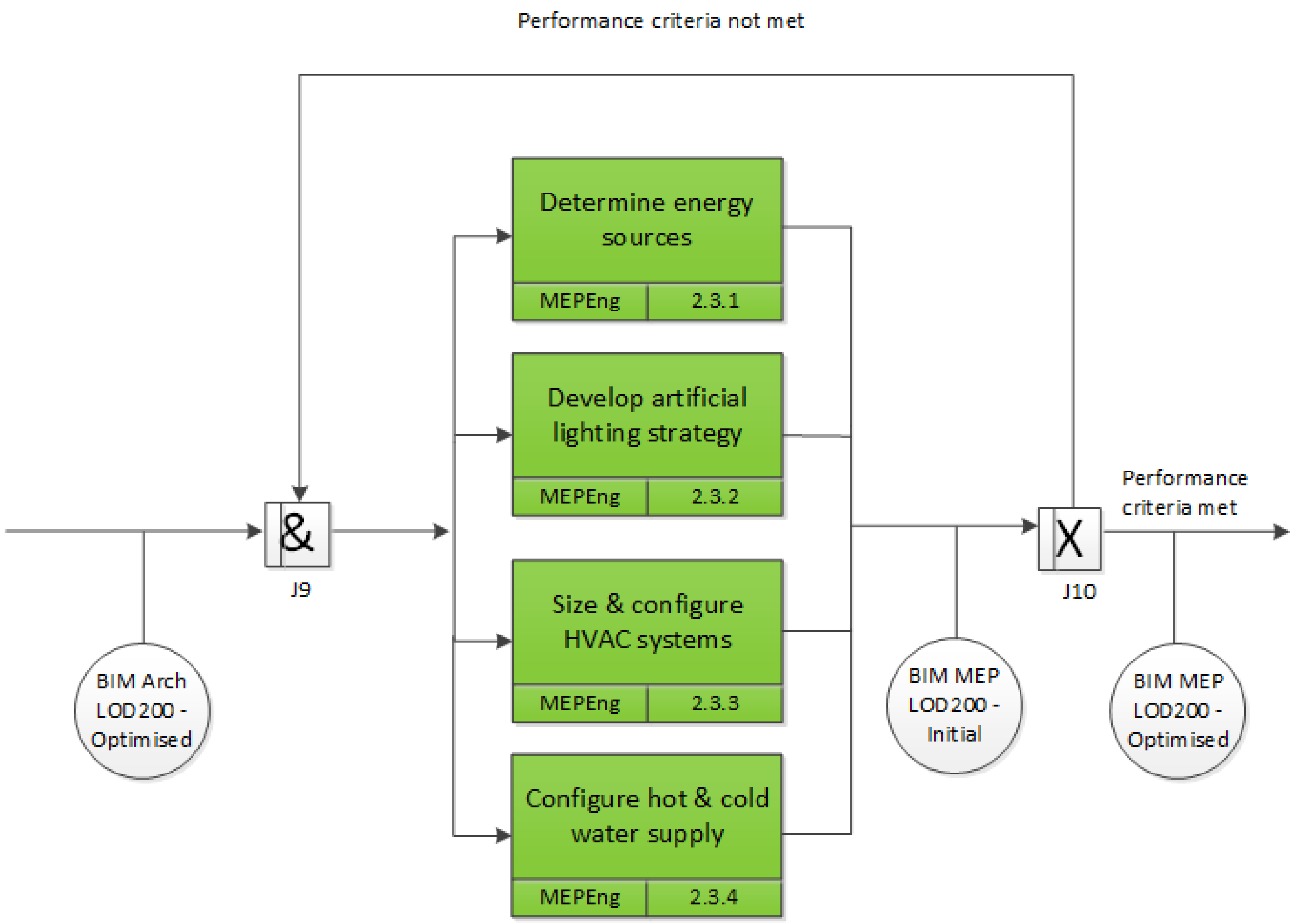


Figure 6.11 Decomposition of UOB 2.3 "Configure mechanical services" [Green UOBs]

6.3.2. Narrative 2: From sketch design to concept sign-off [Blue UOBs]

An Architect/Sustainability Consultant (CS3) described the process of developing the brief from sketch design to concept design (see Figures 6.12, 6.13, and 6.14).

1. The first task was to develop the architectural proposal in 2D sketches based on previous projects and rules of thumb. In the meantime the Architects performed a preliminary PHPP assessment to gain a rough understanding of the building performance. The drawings were issued in the CDE's shared folder to be accessed by the rest of the design team.
2. After these sketches were reviewed by the MEP Engineer, a meeting was arranged for them to comment on those, and make suggestions for improving performance. The outcome of this meeting were marked-up 2D drawings.
3. The Architects, then, amended the drawings according to the MEP Engineer's instructions, and uploaded them to the CDE. The MEP Engineer downloaded those, and performed a dynamic BPA simulation of the architectural design proposal, and sent feedback to the architect. This iterative process continued until the performance criteria for building form, orientation, and openings were met, and agreed. In this example, the process required three weekly meetings between the Architectural team and the MEP Engineers.
4. When both stakeholders reached an agreement, the Architects developed, and issued, more accurate drawings, and then, the MEP Engineers developed the mechanical systems' proposal according to those.
5. This task was followed by a coordination exercise to determine whether the two models (Arch and MEP) had clashes.
6. By the end of the preliminary design stage, the Client approval, concerning the form and fabric of the building, was required.
7. When the Client approved the aesthetics, and performance, of the building fabric, the Architect developed the Revit model that included geometry, dimensions, elevations, materials, spaces, volumes, numbering of elements, ceiling, and voids. This model was, then, shared with the rest of the Project Team to begin with their concept design tasks.

8. The next meeting included the rest of the design team members, as shown in Table 6.2. The iterative process continued until all the proposals were developed to LOD200, and agreed, with the rest of the design team.
9. When all stakeholders reached an agreement, the Client reviewed, and approved, the design proposal. The Client, then, signed-off concept design stage.

BIM software was not utilised in this case study for building massing (UOB 2.1.1), instead the Architects utilised Revit for authoring the fabric and layouts of the building (UOB 2.2.1, 2.2.2., 2.2.3). The following description attempts to align Narrative 2 with Narrative 1 so as to identify common processes, and alternative processes, in order to inform the IDEF3 model accordingly.

Step 1 aligns with the UOB 2.1.1 "*Build massing model*". In this case, the Architects instead of using Revit to construct the building mass, preferred delivering 2D hand drawings. Furthermore, the Architects played a dual role, as Sustainability Consultants, performing a preliminary assessment in PHPP (PassivHaus Planning Package). Also, rules of thumb and previous experience informed their decisions. Step 2 aligns with UOBs 2.1.2., 2.1.3, and 2.1.4, where the MEP Engineers undertook the role of the Sustainability Engineer. The meeting between the Architect and the MEP Engineer aligns with Junction (J4), when the advice of the Sustainability Engineer amended the form, orientation, and location on site, creating a loop in the design process, until the building mass was optimised. Step 3 corresponds to UOB 2.2, when the Architects amended their drawings, built a BIM Arch LOD100, and shared it. This iterative process continued until the BIM LOD200 was optimised and the two parties agreed that the sustainability criteria were met (J8). Step 4 aligns with UOB 2.3 resulting in the BIM MEP LOD200 optimised model. Step 5 presents the need for an additional function (UOB 2.3.5 "*Coordinate drawings*"). In this case, the Architect also played the role of the BIM Coordinator. The outcome of this function was a BIM LOD200 preliminary model. Client approval (Call-and-Wait) was needed (step 6) before the rest of the Project Team (Table 6.2) started authoring their BIM proposals (steps 7, 8). Step 9 describes a multidisciplinary design optimisation process (UOB 2.4

"*Develop holistic concept*"), where structure, infrastructure, systems performance, and cost estimation occurred concurrently. Once the BIMs were coordinated (UOB 2.3.5), the Client Approved (Call-and-Wait), and Signed-off Concept Design Stage (Call-and-Continue). As a result, the IDEF3 model, developed by Narrative 1, has been amended to reflect these changes.

Table 6.2 Design team's attendees once the building fabric was optimised (J8-J9)

Design Team	***Information requirements***
Lead Designer - Architect	Architectural drawings, Revit model
Passivhaus Designer	PHPP analysis
Contractor	Cost information, buildability, construction sequencing
Cost Estimator	Cost assessment
Structural and Civil Engineers	Structural proposal, beam sizing
MEP Engineer	System proposal, IES analysis
Client Representative	Approval
Timber Specialist	Brief requirement

Figures 6.12, 6.13, and 6.14 show the workflows amended by Narrative 2. Figure 6.14 has been developed combing the findings from Narrative 2 with the Schedule of Services for Concept Design, RIBA stage 2 (see Chapter 5, Table 5.4).

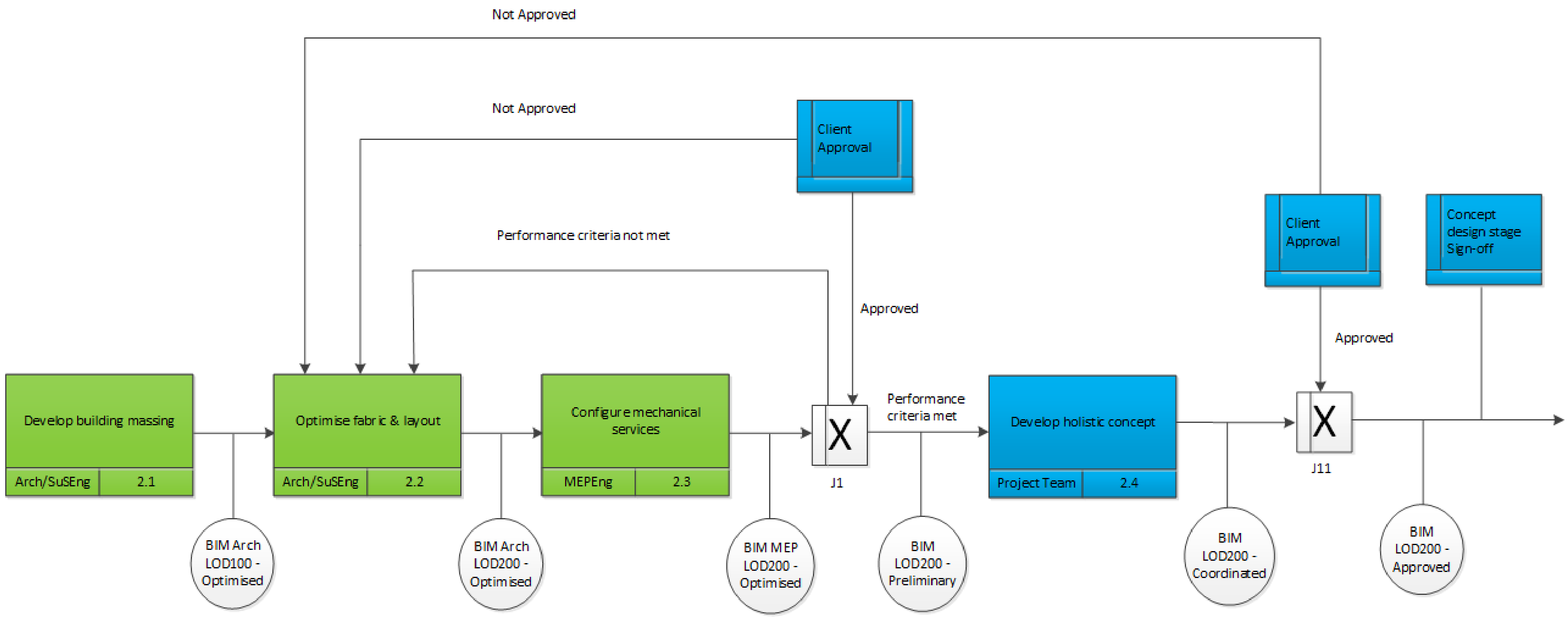


Figure 6.12 UOB 2 "Develop concept design" decomposition amended by Narrative 2 [Blue UOBs]

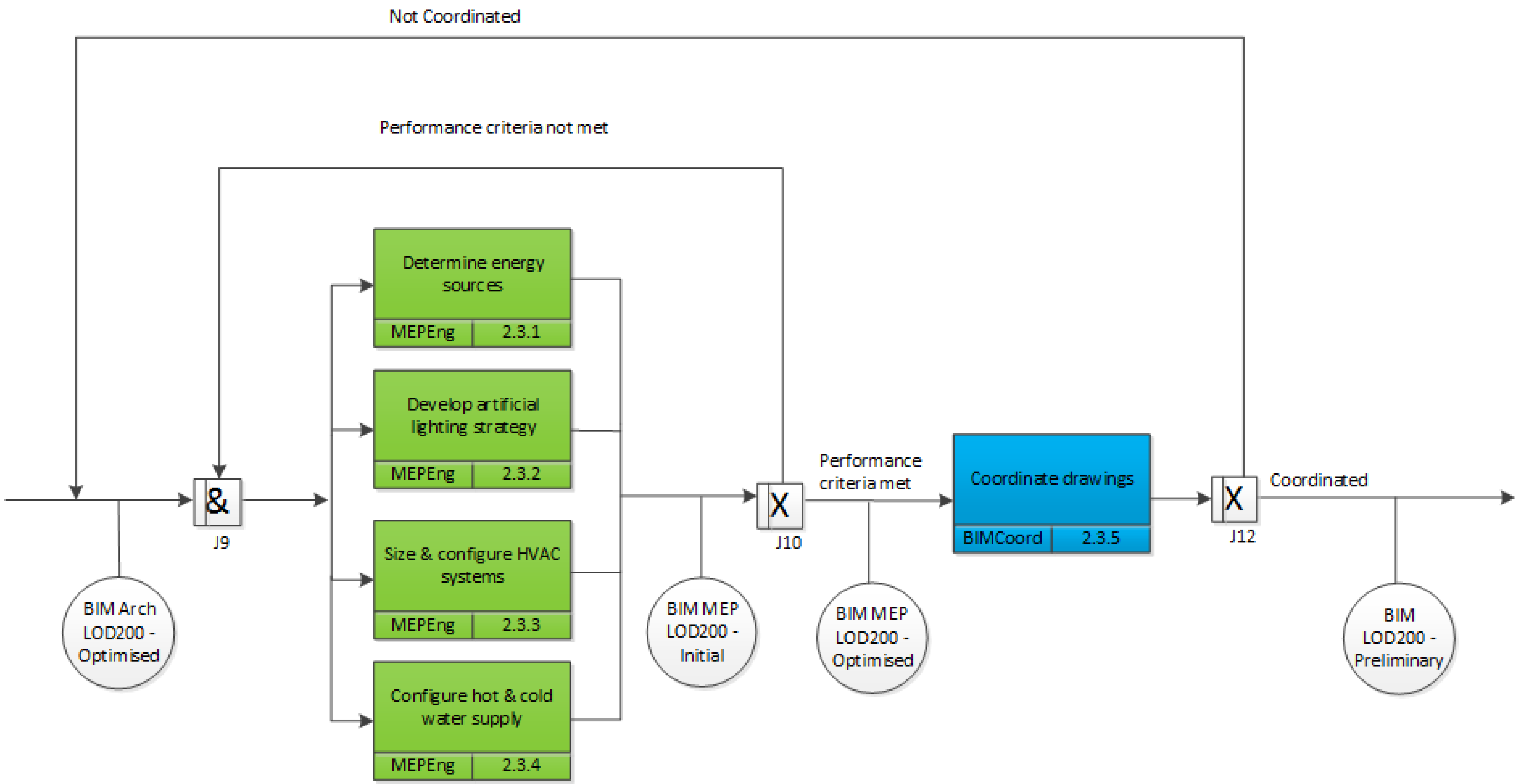


Figure 6.13 Amendments to UOB 2.3 "Configure mechanical services" based on Narrative 2 [Blue UOBs]

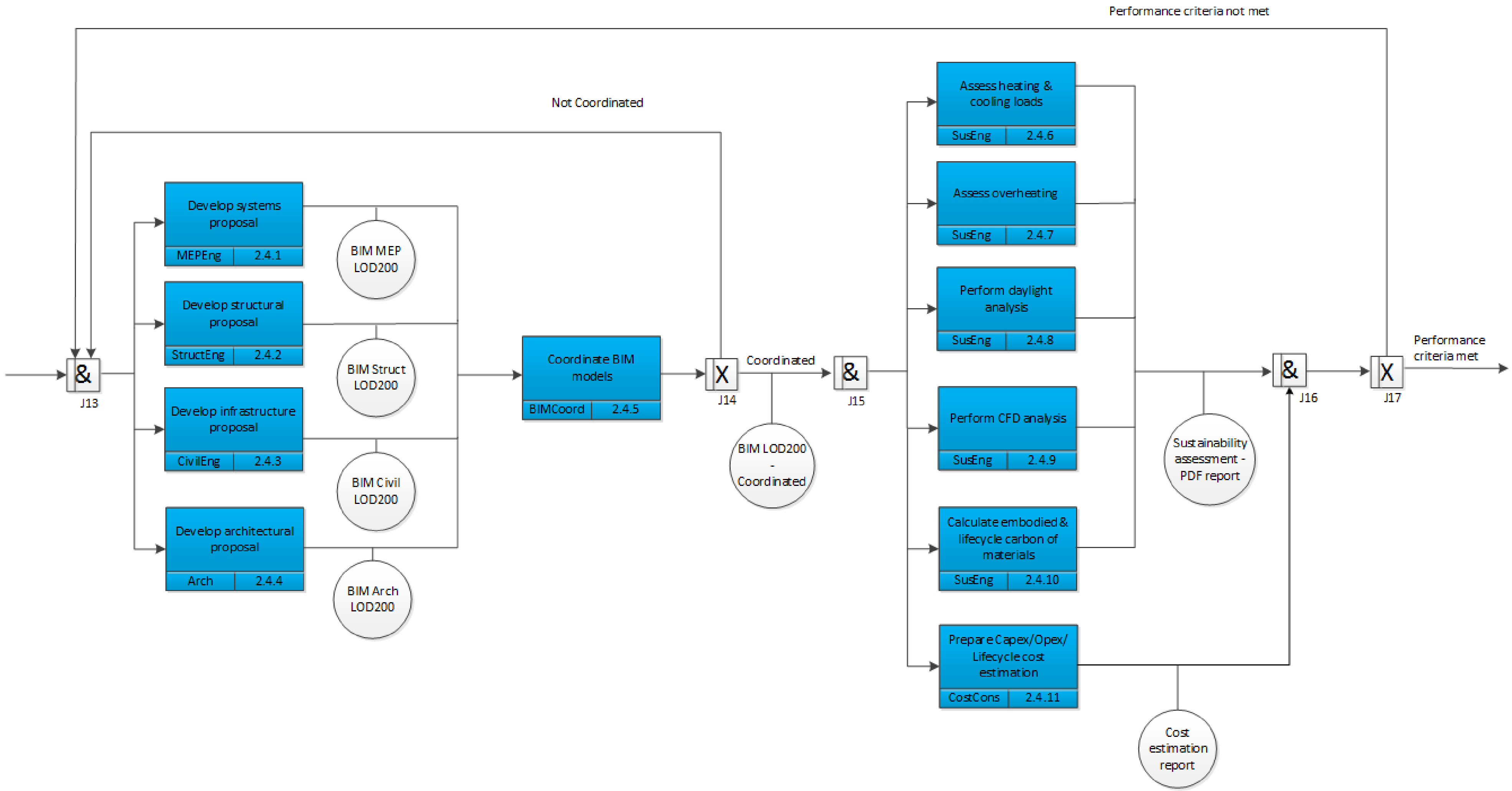


Figure 6.14 UOB 2.4 "Develop holistic concept" based on Narrative 2 and Table 5.4 (Schedule of Services for concept design) [Blue UOBs]

6.3.3. Narrative 3: Feasibility studies of scheme design during briefing [Purple UOBs]

An Architect/Sustainability Consultant (CS3) described the process of assessing the feasibility of scheme design as part of the brief's requirements (see Figure 6.15).

1. The Architects received the Client's brief. Among the other requirements, there was the request of having roof lights and a green roof.
2. The Architects performed thermal and solar analysis in PHPP, and in the meantime, the MEP Engineers simulated the daylight performance of the roof lights in IES-VE software. The roof lights were found to be an inappropriate solution because they were causing overheating during the summer months.
3. The Architects asked again for the advice of the MEP engineers regarding the glass area required for daylighting and the free area for ventilation, and then, designed the windows' geometry according to those recommendations.
4. After that, they presented the revised elevation design to the Client, and it was rejected for aesthetic reasons.
5. This iterative process continued until the adequate balance between daylight, solar, thermal, and ventilation requirements was found to be satisfactory for the Architects and the MEP Engineers.
6. The decision was signed-off only when each member of the design team approved the result.

This incident's description needs to be translated to a higher level of abstraction so as to inform the IDEF3 model. The incident focuses on the UOB 2.2 "*Optimise fabric and layout*". A completed scheme design was a prerequisite to move to this step of the process. In this incident, the Architects undertook the role of the Sustainability Consultant, and Passivhaus Certified Expert. For this reason, they were able to undertake part of the duties of the Sustainability Engineer, such as the Solar analysis, to identify the overheated areas of the building (Step 2). Thus, UOB 2.2.7 "*Perform solar analysis"* has been added to the decomposition of UOB 2.2. Step 3 aligns with UOB 2.2.1, and "*Client Approval*" (Call-and-Wait Action) has been added to the model, to correspond to the aesthetics approval before moving to the performance assessment functions (Step 4). The rest of the duties of the Sustainability Engineer's role were undertaken by the MEP Engineering team. Those were daylight, ventilation, and thermal performance analyses (Step 5), and they align with the previous incident's UOBs 2.2.4, 2.2.5, and 2.2.6. Finally, Junction (J8) is translated as the sign-off of the optimisation of fabric design, where the Architect, Client, and Sustainability Engineers approve the concept and agree that the design criteria are met (Step 6).

Figure 6.15 shows the amendments to UOB 2.2 "Optimise fabric and layout" to accommodate the lessons learnt from Narrative 3.

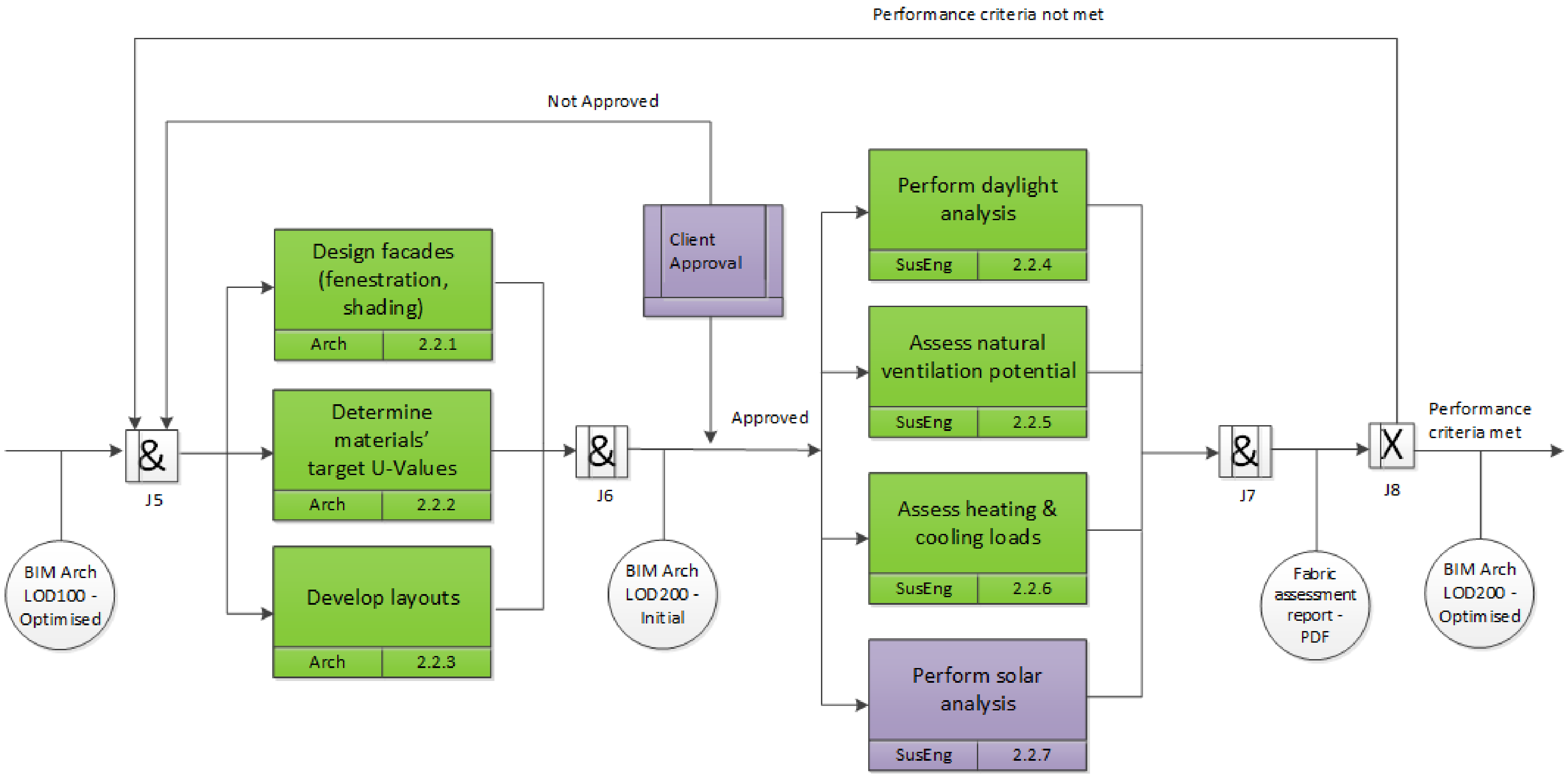


Figure 6.15 Amendments to UOB 2.2 "Optimise fabric and layout" based on Narrative 3 [Purple UOBs]

6.3.4. Narrative 4: Early sustainable window design

An Architect/Sustainability Consultant (CS2) described interrelated design issues of designing the building fabric at early design stage. These tasks resulted in achieving a successful balance between daylight factors and overheating, based on an iterative cycle of trial and error. This example is of a typical classroom of a university building.

1. Based on experience from previous projects, the Architect designed 20% of window to wall ratio so as to achieve the daylight factor required, and 10% of free area for natural ventilation. An additional 5% of free area was required for night ventilation, but this part of the façade had to be covered with louvers for security reasons.
2. These rules of thumb were, then, tested with a dynamic BPA software tool, and then, amended until the desired outcomes were achieved.

This description focuses on UOB 2.2.1 “*Design facades (fenestration, shading)”.* For the implementation of this function, the Architect considered rules of thumb and previous experiences in order to maximise daylight and natural ventilation inside the building’s spaces. Shading devices were utilised to control glare and overheating, and also for security reasons (Step 1). The Interviewee also validated UOBs 2.2.4 to 2.2.7, which required the use of a dynamic BPA simulation software package, by a Sustainability Engineer, in order to achieve accurate results regarding the performance of the fabric. No amendments to the developed models are required as a result of this description (see Figure 6.15).

6.3.5. Narrative 5: Testing for robustness to climate change

An Architect/Passivhaus Consultant (CS2) described the sub-processes and information requirements needed in order to calculate the synergies between overheating and building robustness (see Figure 6.14).

1. The Architectural team used the weather files from 87 years in the future (provided by the Client), and entered them into the PHPP spreadsheet to calculate overheating and lifecycle carbon. The limitation of this software tool is that it calculates the whole area as one massive room (thermal zone). The

Interviewee noted that more detailed dynamic BPA simulation was needed in order to model particular heating scenarios in the future.

2. Those simulations resulted in determining the design of adjustable shades that protect the building from overheating when temperature levels increase.

The description of this incident aligns with UOB 2.4 "*Develop holistic concept*" (see Figure 6.14). Testing for robustness to climate change is an exceptional case of assessing the adaptability to the environment in weather conditions in the future. Essentially, it consists of undertaking simulations for thermal, daylight, CFD, and carbon emissions (UOBs 2.4.6 to 2.4.11) utilising weather files especially developed to contain information for approximately 100 years.

6.3.6. Narrative 6: Ductwork mismatch with English Heritage compliance [Yellow UOBs]

An Architect (CS4) described a process, which he suggested saved a significant amount of time, and assisted in achieving the project programme without delays.

1. The design team decided to lower the ceiling height in order to allow for more services that were needed to improve the thermal performance of the space. That was considered essential due to the air changes and cooling loads needed to accommodate the amount of people expected to occupy the space.
2. When the English Heritage consultation officer was walked virtually into the Navisworks model, he completely disagreed with those changes.
3. Since the design team could not fit the amount of ductwork required to reach the cooling targets in that room, a compromise was made that the room would potentially overheat at certain times a year. The following excerpt emphasises the time savings achieved by implementing BIM:

> *"if needed to submit an alternative proposal provided planning, section and detail, that could have taken two weeks out of the programme for us, and then, two weeks to decide whether we should change it, we view it, and then, if everything was ok, we would have issued the drawings like that next week…" (CS4/Architect)*

Furthermore, the Interviewee discussed the importance of seeking approval from the local planning authorities (for the coordinated design solution), before performing a variety of BPA, which can be time consuming.

This description aligns with UOB 2.4 "*Develop holistic concept*" (see Figure 6.14). It has been argued that compliance with Building Regulations is prioritised over sustainability performance, and thus, acts as a constraint in the SBD process. The Interviewee discussed the benefits of having a coordinated BIM at concept design stage. A "*Planning Approval*" Call-and-Wait has been added to UOB 2.4 to respond to this need. Figure 6.16 shows the changes to the decomposition of UOB 2.4.

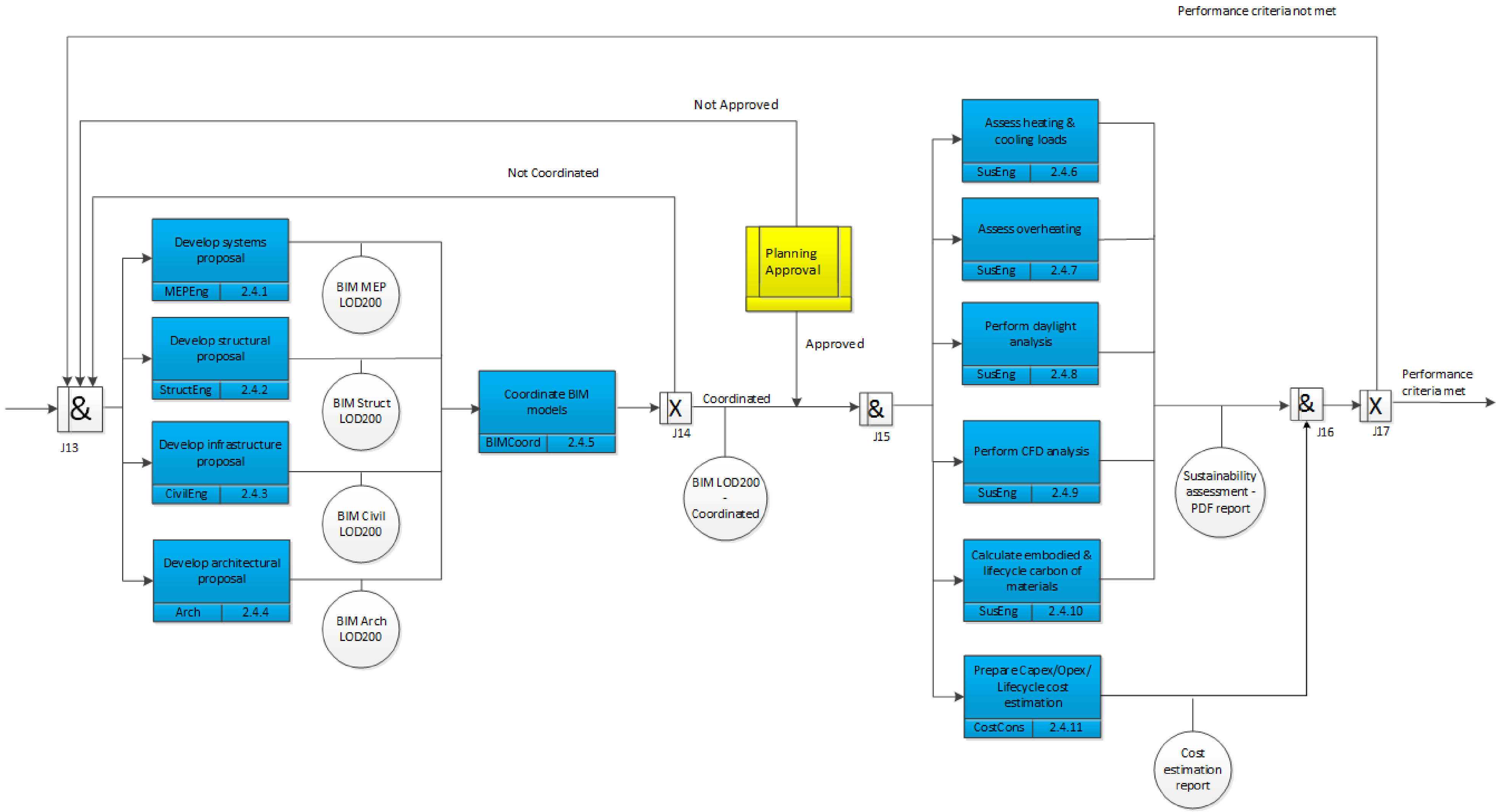


Figure 6.16 Amendments to UOB 2.4 "Develop holistic concept" decomposition due to Narrative 6 [Yellow UOBs]

6.3.7. Narrative 7: Temperature range requirement led to high energy loads [Orange UOBs]

An Architect/Sustainability Consultant (CS5) described how the Client's occupancy requirements for a specific temperature range led to failing to achieve the sustainability aspirations for efficient energy performance.

1. The Client requested a temperature range between 18 to 28 degrees Celsius. It was explicitly stated that the peak temperature should not to be exceeded under any circumstances.
2. The Architectural team authored a spatial model (BIM LOD100) that allocated rooms and volumes, and embedded the performance criteria within it (e.g. natural ventilation, number of occupants, type of activity, hours and days of operation) as included in the Client's brief.
3. The MEP Engineers/Sustainability Engineers assessed the building's performance (in IES-VE software) and advised the Architectural team (regarding openings, sizing, orientation etc.).
4. The Architectural and MEP Engineering teams tested the alternative design options aiming to achieve the 18-28 Celsius target through an iterative process.

Striving to address the brief's requirement, the BPA resulted in having a larger energy load than expected, which led to losing several BREEAM points in the ENE1 section (5 out of 15 credits were achieved). Thus, to achieve the BREEAM Excellent target, the Project Team adopted compromise solutions such as water recycling, low-flash volumes, and bicycle racks. This solution was considered unsatisfactory and was described as "*cheating*" by the Interviewee. The building resulted in having poor environmental performance, despite achieving the BREEAM certification. The Interviewee suggested that the solution to this problem is to educate the Client during briefing (RIBA stage 1) in order to set realistic, and achievable, performance targets. Learning from that unsatisfactory experience, the Interviewee described better ways to deal with similar situations. The first thing that the Architects and Sustainability Engineer do now is to model the building (in IES-VE software) for 365 days per year in order to identify the areas that exceed the requirements set. Then, depending on the occupancy schedules and use of the space, they consult the Client. For example, if it is a personal office, the occupants can accept the temperature to be slightly warmer, for a few days per year, because the individual has control over the environment, and thus, it can be easily adapted. On the other hand, in a lecture theatre, they would implement a local solution for cooling in order to restore the thermal comfort when needed. The following excerpt expresses the Interviewee's view in his own words:

> *"That analytical full modelling scenario permits us to isolate problems and come up with local solutions for them… analytical modelling at the end stage of design enables to make those critical decisions. If you do it too late in the process, you end up with half-baked solutions, like photovoltaics, to make up for the mistakes. A better solution takes more work upfront, and more understanding upfront, to be able to do that." (CS5/*Architect/Sustainability Consultant)

This description aligns with UOB 2.1 "*Develop building massing*" (Figure 6.9), and UOB 2.2 "*Optimise fabric and layout*" (Figure 6.15). Steps 1 and 2 align with the information requirements to build the massing BIM (UOB 2.1.1). After the Sustainability Engineer's analysis and advice, the Architects build a BIM Arch LOD200 (UOBs 2.2.1 to 2.2.3). Then, the BPA is assessed in an iterative manner based on pre-determined sustainability criteria (J8).

After reflecting on the incident, the expert suggested that Client Approvals are needed, in case the performance criteria are not met, and compromise solutions need to be found. This corresponds to Junctions J4, J8, and J17 of the IDEF3 process model. It means that exceptions to override the performance criteria set during briefing should be added in case the Client agrees with the alternative solutions suggested by the SBD experts. As a result, UOBs 2.1, 2.2, and 2.4 decompositions have been adapted to reflect that by adding "*Client Approval*" Call-and-Wait UOBs before the sustainability criteria are assessed utilising BPA tools. Figures 6.17, 6.18, and 6.19 illustrate the changes to the IDEF3 process model's diagrams.

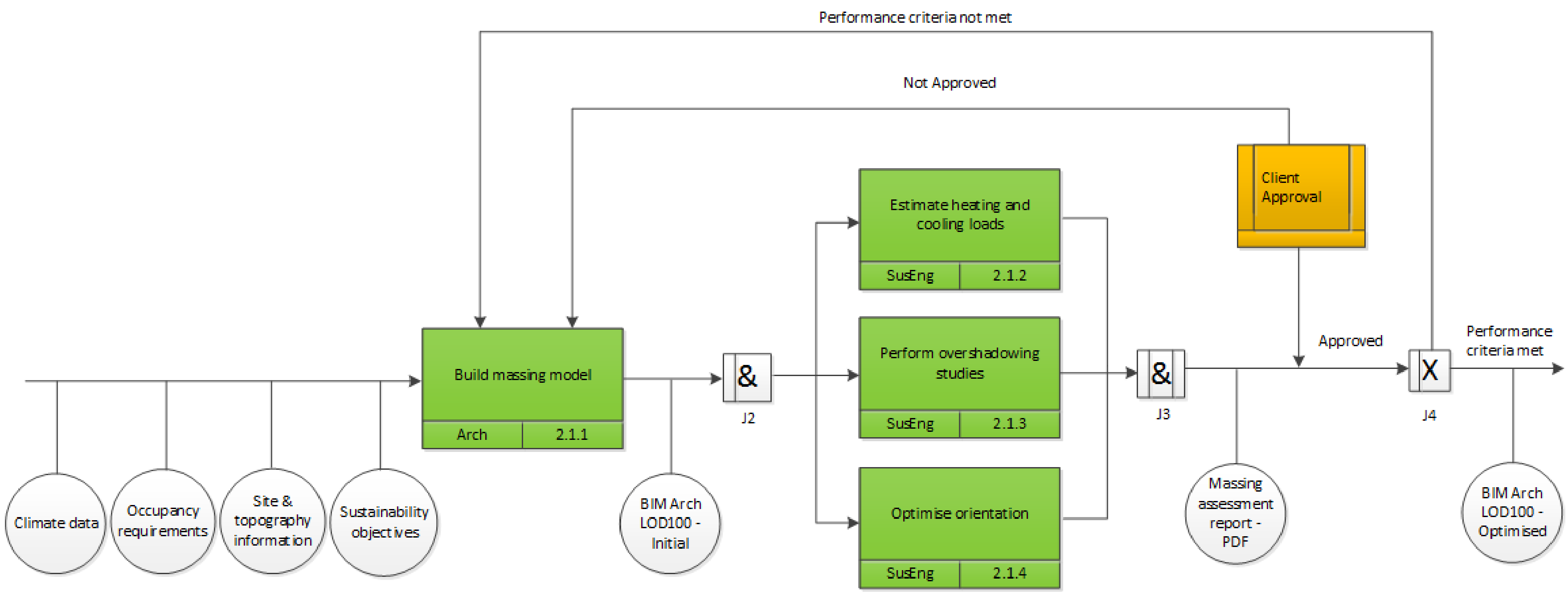


Figure 6.17 UOB 2.1 “Develop building massing” decomposition amended according to Narrative 7 [Orange UOBs]

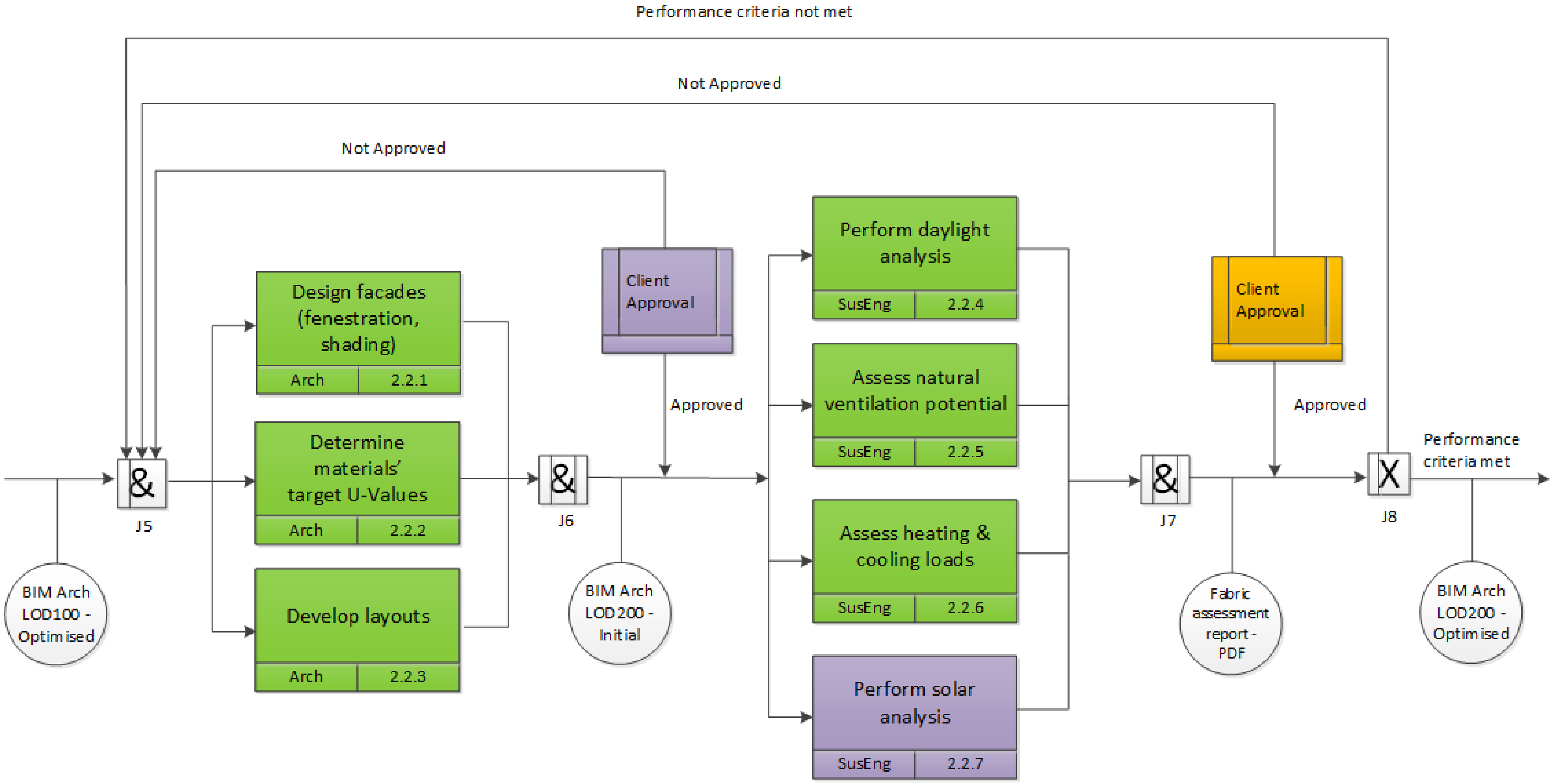


Figure 6.18 UOB 2.2 "Optimise fabric and layout" decomposition amended according to Narrative 7 [Orange UOBs]

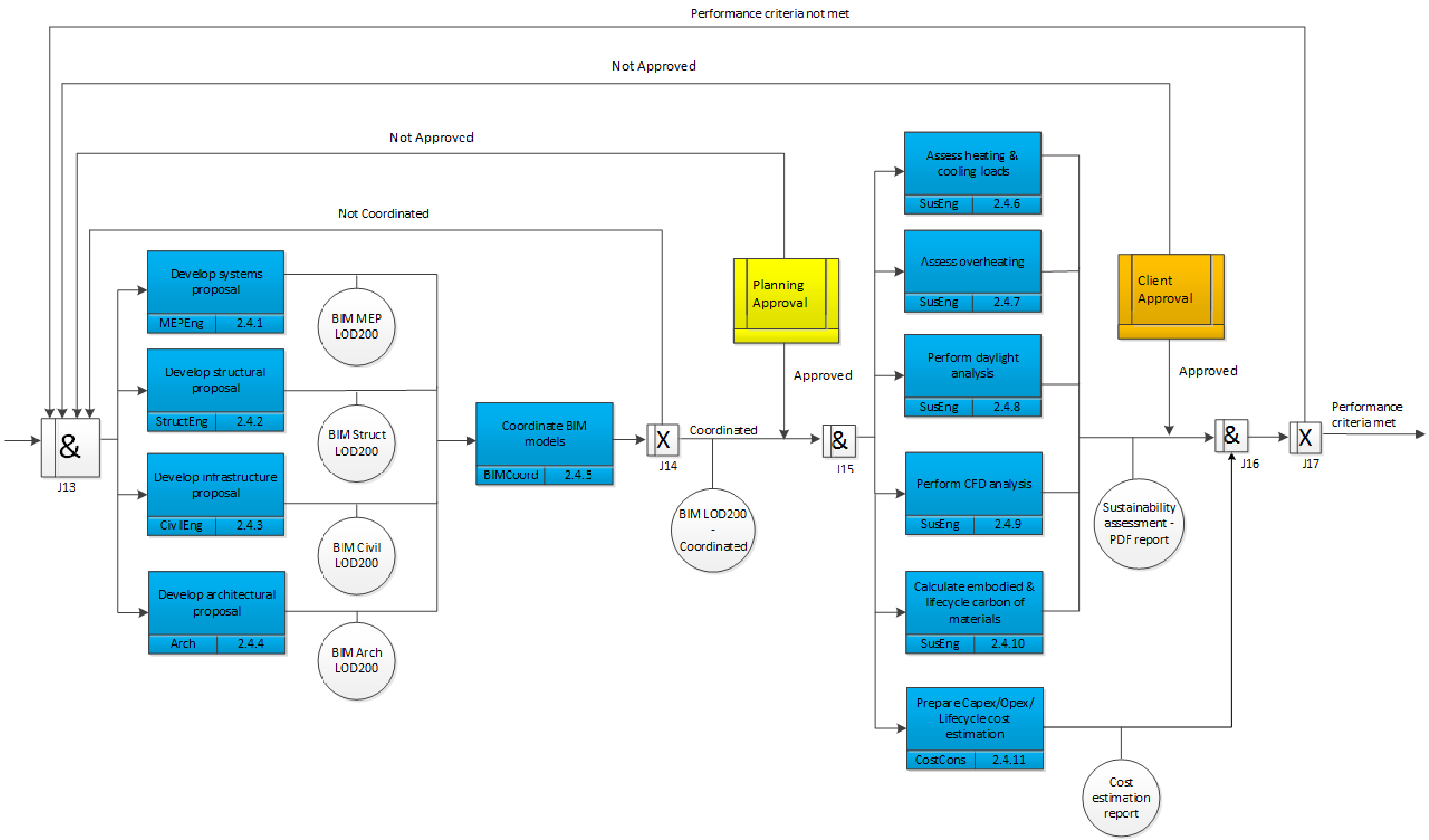


Figure 6.19 UOB 2.4 "Develop holistic concept" decomposition amended according to Narrative 7 [Orange UOBs]

6.3.8. Narrative 8: Optimising building fabric through design-assessment iterations

An Architect/Sustainability Consultant (CS6) described the process implemented to optimise the building fabric, utilising BIM software (Revit) and BPA tools (IES-VE).

1. Firstly, the Architect loaded the performance criteria for the rooms, and then, shared the BIM (Arch) with the MEP Engineers/Sustainability Engineers.
2. The MEP Engineers performed the environmental analysis based on their BPA model (IES-VE), and returned reports (PDF) and graphical outputs (snapshots of their model). The key decisions at this stage were the source of energy, materials along with their quantities, and the size of the building.
3. The design process occurred in a seven day rolling cycle so that the Architectural model was amended to respond to the MEP Engineers' analyses. In the meantime, everyday dialog took place to avoid surprises by the end of the week. An open dialog took place through phone conversations and exchanges of sketches "*without worrying about liability*".
4. By the end of concept design (RIBA stage 2), the room performances needed to be determined. To achieve that, solar shading analysis, heating and thermal analysis, and overshadowing analysis were performed (by a Sustainability Engineer).

This description validates the IDEF3 model's UOBs 2.2 and 2.4 decompositions (see Figures 6.18 and 6.19 respectively). The Architect develops the BIM Arch LOD200, designing each room as a separate thermal zone and enters the occupancy requirements (e.g. schedule, number of people, days of occupancy per month, hours of occupancy per day, types of activities, comfort zone temperatures) (UOB 2.2.3). Furthermore, the openings and target U-Values of materials are determined (UOBs 2.2.1 and 2.2.2). The Architectural BIM is, then, uploaded to the CDE (Step 1). The Sustainability Engineers perform the environmental performance analysis (UOBs 2.2.4 to 2.2.7) utilising dynamic simulation software, and share PDF reports and snapshots of the model through the CDE (Step 2). The iterative process of developing, and assessing, the design continues until the Client's aspirations are satisfied (Step 3). Before the concept design stage is signed-off, the thermal performance, heating and cooling loads, daylight, CFD, and lifecycle carbon analyses (UOBs 2.4.6 to 2.4.10) are optimised (Step 4). The Interviewee (CS6/Architect/Sustainability Consultant) stressed the importance of assessing building performance gradually, for architectural design, in order to make informed decisions during conceptualisation.

6.3.9. Narrative 9: Unmanageable amount of clashes during BIM coordination

A BIM Coordinator (CS7) reported his experience in a large-scale project. His role during the process was to review the various BIMs on a daily basis and run the clash detection. This role requires to have an overview of the process so as to ensure that the BIM Execution Plan (BEP) is followed, and the submissions are delivered on time. When uncertainty arises concerning an area of the building in the federated model, the role requires reviewing the Architectural, Structural, and MEP Engineering models to resolve the issue. Furthermore, by using Solibri software, the BIM Coordinators, can create rules to assist them in making these distinctions. The following comment discusses the Interviewee's role in identifying clashes in building design:

> *"…you should be able to recognise what is actually a clash. A beam going through a wall is not a clash, it's supposed to do that. It is about understanding how a building works and what is genuinely a clash." (CS7/ BIM Coordinator)*

1. The BIMs' coordination took place weekly, from the early stages of design. Initially, the model was generic consisting of just roofs and walls (as blocks) with no definition of materials.
2. The method used to review the models was on a floor-by-floor basis, by overlaying the Architectural model, the Structural model, and the MEP model.
3. A notable issue discussed was the fact that the Architects were reluctant to remove the structural elements in their model in order for it to look right. As a result, duplication of structural elements was found in the model during coordination. This fact overloaded the coordinated BIM and hindered the detection of the actual clashes occurring between building elements.

This Narrative corresponds to several functions of the IDEF3 model (see Figures 6.17, 6.13, and 6.19). The first one is UOB 2.1.1 "*Build massing model*" (BIM Arch LOD100)

(Step 1). Steps 2 and 3 describe the process of coordinating the various BIMs (UOBs 2.3.5, and 2.4.5). For large projects, the BIMs (all models) is broken down into zones, in this case floor-by-floor, so that it becomes easier to manage. The way the Architectural model is built has been found to be critical for efficient coordination (Step 3). Therefore, the Interviewee suggested that coordination exercises, of BIMs, should start from the early stages of design. Furthermore, clear allocation of modelling responsibilities (for the BIM elements) should happen before design commences. It was argued that a Design Responsibility Matrix (DRM) gives added-value at later stages, when clash detection becomes even more complex.

6.3.10. Narrative 10: BIM Coordinator's perspective of the SBD process [Red UOBs]

A BIM Manager and Coordinator (CS8) described the standard workflows that take place within an architectural practice.

1. First, the Architects author a geometric model in ArchiCAD.
2. Then, they perform in-house BPA utilising Graphisoft's EcoDesigner software. Although not NCM accredited, it gives a good estimation without any delays. For this reason it has been found to be very useful for early environmental analysis (e.g. climate analysis, low-energy demand architectural design). An iterative process for optimisation of the building geometry, orientation, and location on site takes place.
3. The model is, then, shared in the CDE (4Projects), in IFC format.
4. After the form of the building is optimised by the Architect (e.g. form, openings, size, shape, location) and the Structural Engineer (e.g. steel, bracing on doors and windows), the MEP Engineer sizes the services.
5. Once the form is optimised, specialist sub-contractors (Sustainability Engineers) receive the Architectural model, and perform dynamic BPA simulation in IES-VE for more accuracy. An iterative process of optimisation follows.
6. Then, the BIM Manager/Coordinator receives the Architectural, Structural, and MEP models, and performs a coordination exercise, in Solibri software, to identify clashes.

7. By the end of Concept Design (RIBA stage 2), a LOD200 COBie (Construction Operations Building Information Exchange) data drop 2 is required. This contains is approximate geometric and location information for all structural elements. More specific information is not included, apart from wall thicknesses, number/type of openings, global location, occupancy, and areas.

Steps 1 and 2 align with UOB 2.1 decomposition (see Figure 6.17); the Architect authors the geometric model (UOB 2.1.1), and then, early environmental assessment is performed (UOBs 2.1.2 to 2.1.4). Junction (J4) corresponds to the decisions' point, which may lead to iteration. UOB 2.2.8 "*Assess performance of structural elements*" and UOB 2.2.9 "*Size structural elements*" (by a Structural Engineer) have been added to the model (see Figure 6.20). Sizing of the building services (Step 4) align with UOBs 2.3.1 to 2.3.4 (see Figure 6.13). Once the 3D models have been optimised individually, the coordination exercise task (Step 6) aligns with UOB 2.3.5 (see Figure 6.13). A COBie Data 2 drop has been added to UOB's 2.4 decomposition (see Figure 6.21), as an output of the concept design stage (Step 7). Figure 6.20 and Figure 6.21 show the amendments to UOB 2.2 "*Optimise fabric and layout*", and UOB 2.4 "*Develop holistic concept*" respectively, according to Narrative 10.

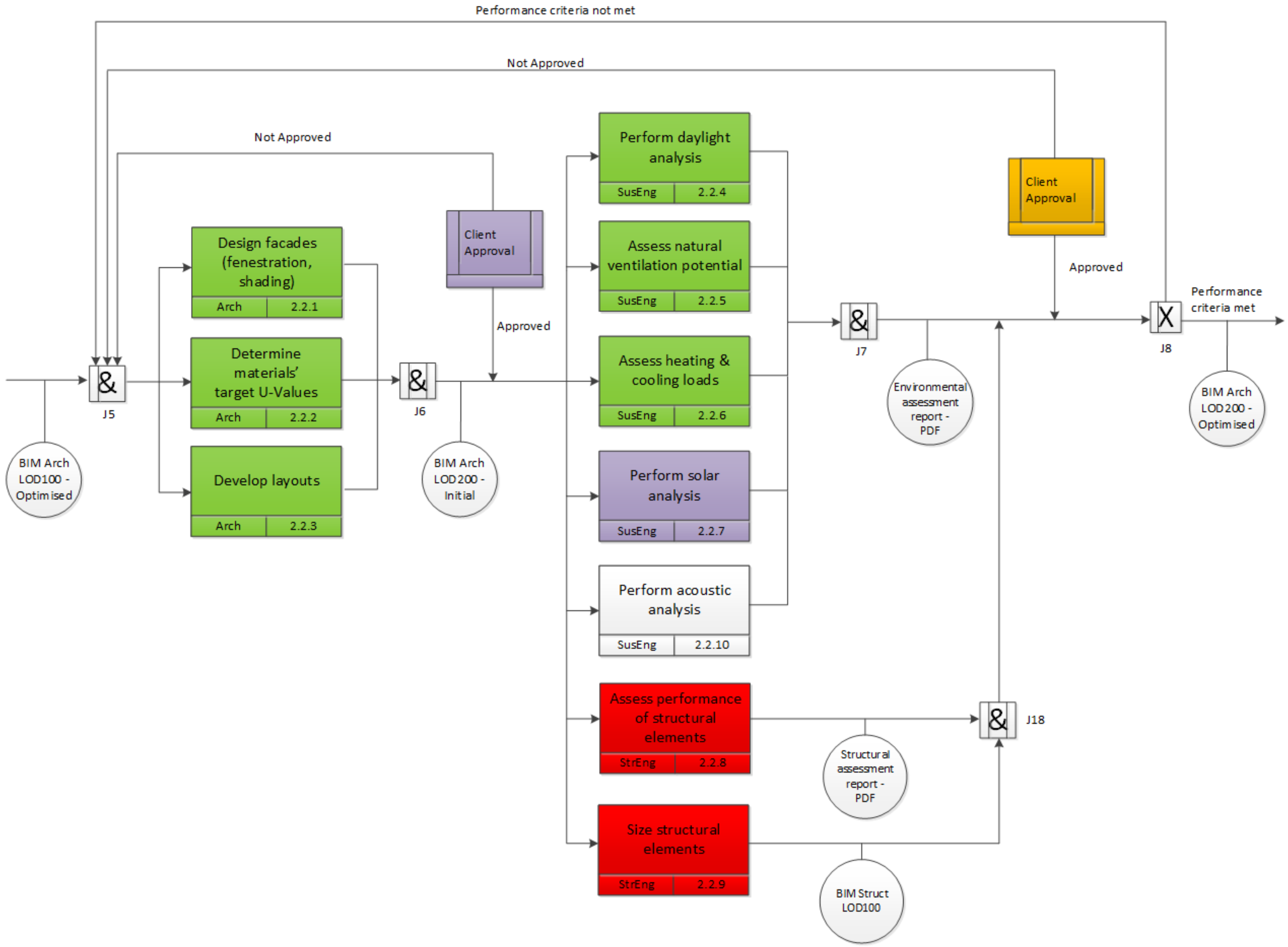


Figure 6.20 UOB 2.2 "Optimise fabric and layout" decomposition amended according to Narrative 10 [Red UOBs]

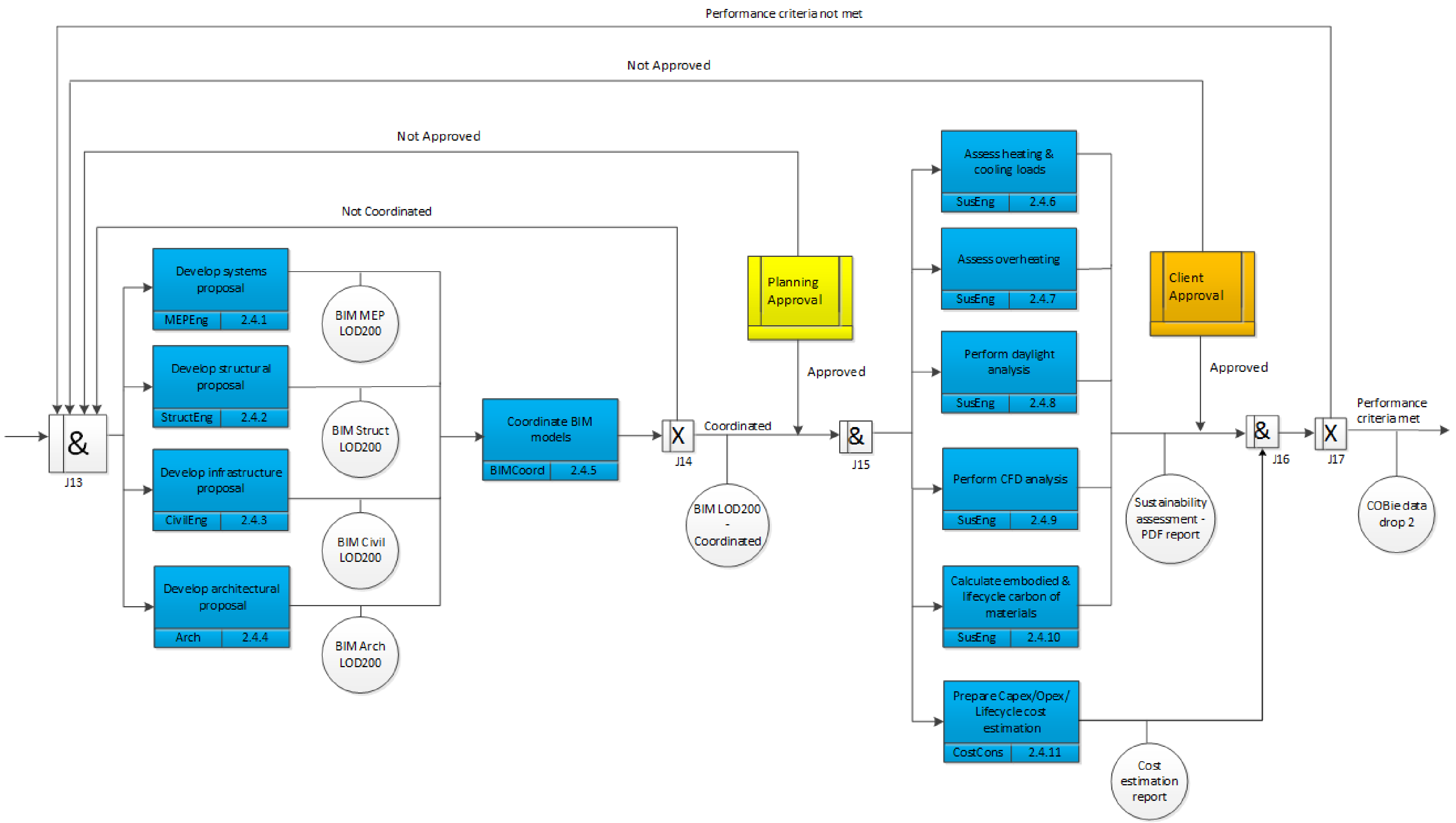


Figure 6.21 UOB 2.4 "Develop holistic concept" decomposition amended according to Narrative 10 [COBie data drop]

6.3.11. Narrative 11: BREEAM Assessment at the early design stages [Grey UOBs]

A BREEAM Assessor/Sustainability Consultant (CS11) described an incident of a design that targeted a BREEAM Outstanding certification. The sustainability goals were the following: (i) zero emissions, (ii) zero carbon, (iii) low impact systems, (iv) timber frame, (v) daylight, and (vi) natural ventilation. The BREEAM objectives were: (i) energy (mandated), (ii) monitoring, (iii) responsible sources materials, and (iv) management credits. The BREEAM Pre-Assessment (design stage) took place at stages 1 and 2 of the RIBA Plan of Work 2013 (briefing and concept design).

1. The BREEAM Assessor was involved at stage 1 (briefing) to assess various scheme design's alternatives so as to reduce uncertainty. In this case, they also undertook the role of the Sustainability Consultant, managing the design team's sustainability roles.
2. The Architects were responsible for materials, layouts, window size and location, access, location of toilets, washing, and basins.
3. The MEP Engineers performed the energy modelling, schematics and metering, electric lighting, and mechanical ventilation design analyses. Furthermore, they were responsible for water quality, pollution, carbon and NOx (mono-nitrogen oxides) emissions. They also undertook the role of the Sustainability Engineer, and assessed daylighting, and natural ventilation.
4. The Structural Engineers focused on the impact of materials of the frame (carbon footprint and thermal mass).
5. The Civil Engineers assessed flood risk, water pollution, and drainage.
6. The Cost Consultant performed a cost assessment, in this case for 50 to 60 years in the future (but usually they do up to 25 to 30 years).
7. Finally, a BREEAM design stage pre-assessment was performed to determine compliance. IES TaP provided a collaboration interface with 4Projects (by Viewpoint). At RIBA stage 2 (concept design), the evidence received was mainly letters of commitment, but specifications were not provided.

The Interviewee argued that the definition of sustainability metrics should be performed before concept design (RIBA stage 2) starts, at briefing (RIBA stage 1), as seen in Step 1. Furthermore, it has been deduced that the Information requirements of the UOBs 2.4.1 to 2.4.11 align with Steps 2 to 6 (see Figure 6.21). UOB 2.4.1 "*Develop systems proposal*" can be decomposed into UOB 2.4.1.1 "*Size HVAC systems*", UOB 2.4.1.2 "*Design artificial lighting systems*", UOB 2.4.1.3 "*Size water supply services*", UOB 2.4.1.4 "*Assess energy consumption*", UOB 2.4.1.5 "*Assess CO_2 and NOx emissions*", and UOB 2.4.1.6 "*Assess water consumption*" (Step 3). UOB 2.4.2 "*Develop structural proposal*" can be decomposed further into UOB 2.4.2.1 "*Size foundations and frame*", UOB 2.4.2.2 "*Design window and door bracings*", UOB 2.4.2.3 "*Assess carbon footprint",* and UOB 2.4.2.4 "*Assess thermal mass*". In addition, it has been found that BREEAM design stage pre-assessment takes place once the performance analysis is completed (J17).

Figures 6.22 and 6.23 show the decompositions of UOBs 2.4.1 and 2.4.2 respectively. These have been created based on the logical patterns (design-assessment) that have been identified from the previous Narratives, and were also stated by the Interviewee during the description of this incident.

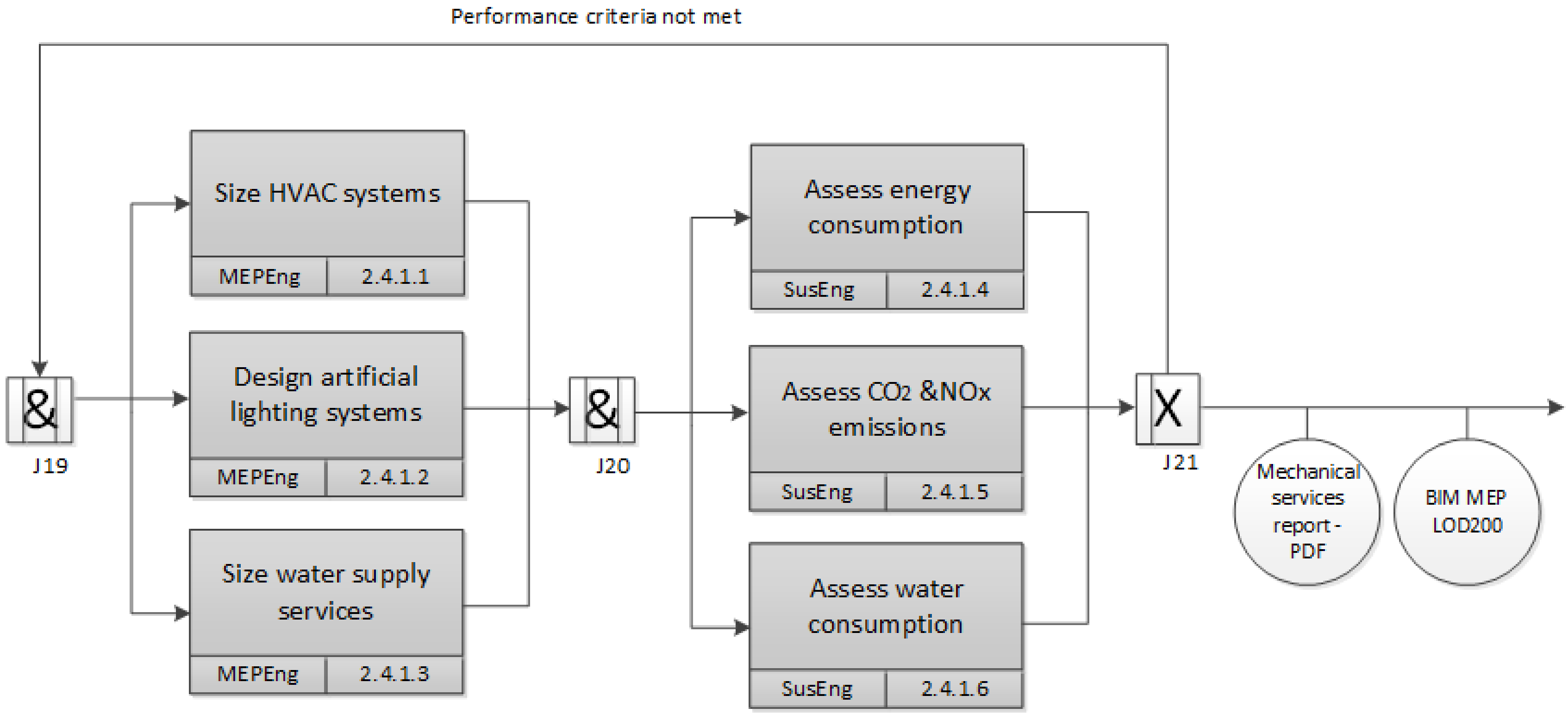


Figure 6.22 UOB 2.4.1 "Develop systems proposal" decomposition developed based on Narrative 11 [Grey UOBs]

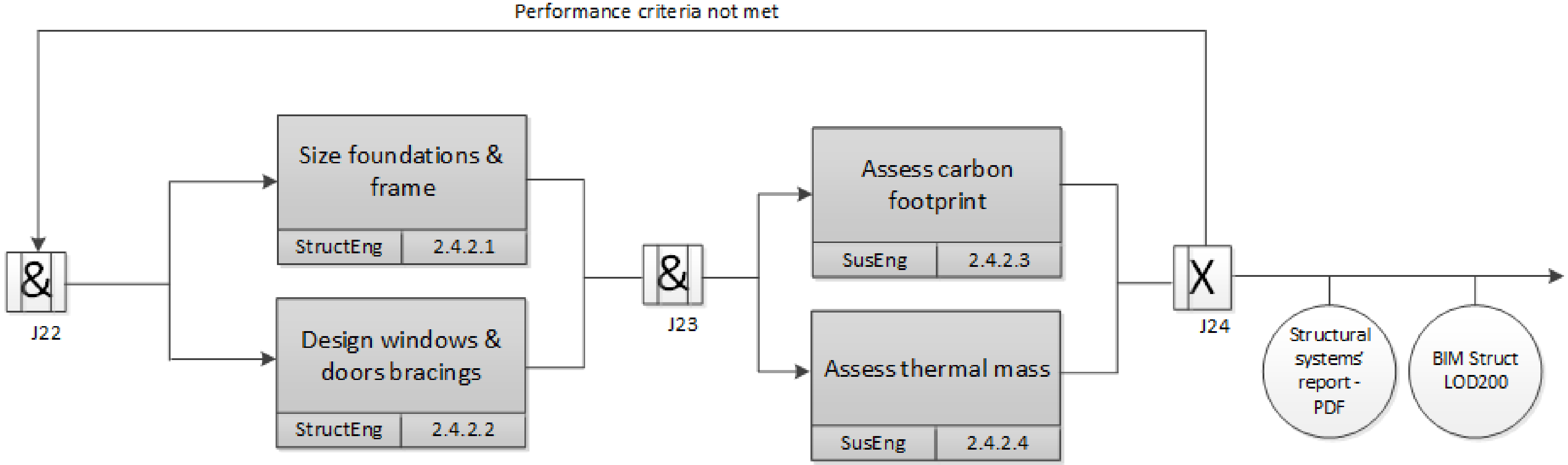


Figure 6.23 UOB 2.4.2 "Develop structural proposal" decomposition developed based on Narrative 11 [Grey UOBs]

6.3.12. Narrative 12: Level 2 BIM maturity - ongoing project [Magenta UOBs]

An Interviewee (CS12/Architect) described the collaborative process of an ongoing project (shopping centre), which had been certified for Level 2 BIM maturity. In terms of sustainability, the target was to achieve BREEAM Excellent or Outstanding. A weekly cycle of exchanging the BIMs was implemented.

1. The Architect noted that building massing design was found to be quicker when it took place with pen and pencil, compared to constructing a BIM; this task aligns with UOB 2.1.1 (see Figure 6.17). The deliverables also included scanned sketches of the building's geometry.
2. The Architect utilised rules of thumb to design in more detail (LOD200), also asking for the advice of the Sustainability Engineer to decide the properties of materials (e.g. U-Values). The output of this task was 2D drawings, taken out of the BIM Arch model (UOB 2.2, Figure 6.20). The Interviewee emphatically stated that: *"the key requirement is 2D drawings".*
3. The model was, then, shared in the CDE, and the Structural Engineers were responsible for determining the thermal mass of the structural frame along with the embodied carbon of the selected materials (UOB 2.4.2). In the meantime, the MEP Engineers designed the ducts, grills, and lights so as to estimate energy consumption (UOB 2.4.1). See Figures 6.23 and 6.22 respectively.
4. Once the specialised BIMs (i.e. architectural, structural, and MEP) were coordinated, the Sustainability Engineers assessed the overheating and solar performance of the building, and produced a report, which they shared with the rest of the design team.

Based on this description, UOB 2.4.12 "*Analyse solar performance*" has been added to UOB 2.4 "*Develop holistic concept*" decomposition (see Figure 6.24).

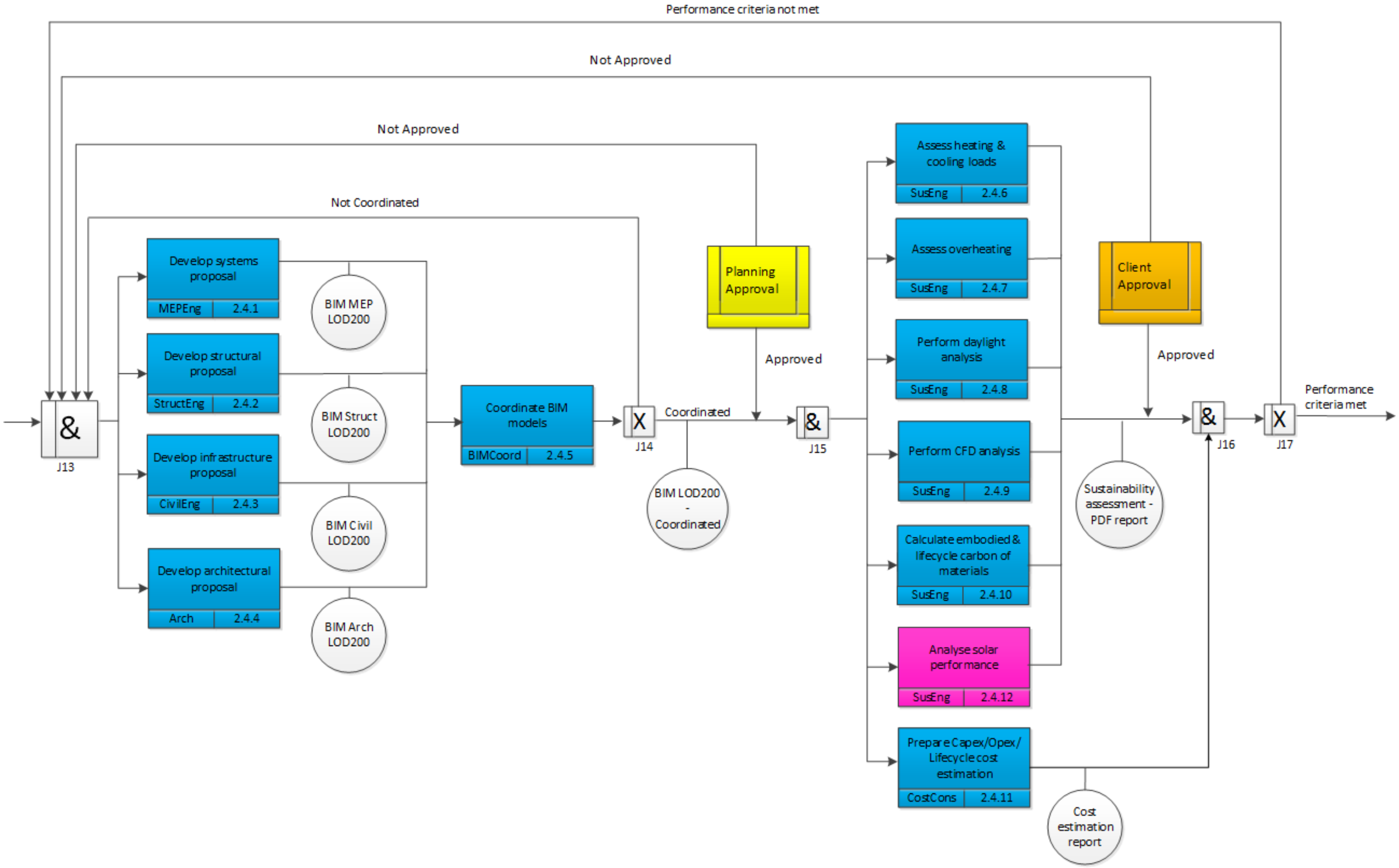


Figure 6.24 UOB 2.4 "Develop holistic concept" decomposition amended according to Narrative 12 [Magenta UOBs]

6.3.13. Narrative 13: Knock-on effects of designing an atrium in an office building

A Sustainability Director/BREEAM Assessor (CS13) described the process of designing an office building. The incident occurred within an integrated design practice, which consisted of a multidisciplinary team of design specialists. Communication occurred through meetings, reports, emails, and Autodesk Glue CDE to comment on design.

1. The information required from the Client was their aspirations regarding the building form, the size of spaces, the activities that would take place within each space, the facilities and services, and the budget allowance. In terms of sustainability, the goals were low energy, specific performance metrics, and environmental rating system (e.g. BREEAM).
2. The first step was for the Architects to produce massing models, and perform environmental analysis such as shadow, solar shading, directly from the BIM (Arch), utilising Revit software. In this example, sensitivity analysis was performed to optimise the building's orientation so as to reduce the heating and cooling loads. The Sustainability Engineers' recommendation was to rotate the building by 90 degrees.
3. Then, the Architects developed the model further working with the façade, to determine insulation values, and design the atrium, and then, shared their BIM with the rest of the design team.
4. The Sustainability Engineers performed daylighting and thermal studies. In this case, they assessed the natural ventilation, thermal mass, heating and cooling loads, and daylight performance. The limitation reported here was that the Architectural model delivered was not appropriate for BPA due to the fact that the thermal zoning was not modelled correctly. As a result, the Sustainability Engineer had to recreate the model in the BPA software: *"that is hardly an issue of the software; it is an issue with the process".* When the analysis was completed, they shared a PDF report, containing their interpretation of the BPA analysis along with recommendations for design changes. The target for the air-tightness of the building was also set at this point.
5. After that, Client approval was required in order to proceed to the next task.

6. Once the demand for energy was reduced, utilising passive design measures, then, active MEP systems were designed in the most efficient way, considering the energy source (e.g. renewables) and the least environmental impact (e.g. pollution).
7. The Interviewee reported that, by the end of Concept Design (RIBA stage 2), the coordinated BIM (LOD200) should contain layouts, types of rooms, building area, floors, orientation, design of the façade, percentage of glazing, types of openings, atrium areas, building form, and building elevation. Furthermore, it was argued that the most critical decisions for concept design are the following: (i) location on site, (ii) orientation, (iii) glazing (location and size), (iv) locations of rooms, (v) solar shading, and (vi) exposed thermal mass of internal materials.

The incident's description validates and informs several of the model's UOBs. Steps 1 and 2 align with UOB 2.1 decomposition "*Build massing model*" (see Figure 6.17) followed by the estimation of heating and cooling loads, solar analysis, and optimisation of orientation (UOBs 2.1.2, 2.1.3, 2.1.4). Steps 3, 4, and 5 align with UOB 2.2 decomposition "*Optimise fabric and layout*" (see Figure 6.20) for developing the building form (UOBs 2.2.1, 2.2.2, 2.2.3), and assessing daylight (UOB 2.2.4), natural ventilation (UOB 2.2.5), heating and cooling loads (UOB 2.2.6), followed by the Client's approval (Call-and-Wait). Steps 6 and 7 are high-level descriptions of UOBs 2.3 "*Configure mechanical services*" and 2.4 respectively "*Develop holistic concept*" (see Figure 6.12).

6.3.14. Narrative 14: Passive design assessment process for fabric optimisation

An Interviewee (Sustainability Director) explained the high-level process of assessing the building fabric, before the MEP services were added to the BIM. This Narrative validates UOB 2.2 decomposition "*Optimise fabric and layout*" (see Figure 6.14).

1. The Architects constructed a massing model in BIM (LOD100), and optimised the orientation and geometry, by iteratively assessing the building as a whole (UOB 2.1).

2. The next step was to assign separate thermal zones for each space and input the occupancy requirements, which were distinct for each thermal zone. Those included massing, proportion of glass, layouts, and orientation (UOBs 2.2.1 to 2.2.3). At this stage, dynamic BPA simulation software was utilised to assess environmental performance (daylight and heating) (UOBs 2.2.4 to 2.2.7).

6.3.15. Narrative 15: Duplication of work for sustainability assessment

A Sustainability Engineer/BREEAM Assessor reported the process problem that occurred due to the fact that the Architectural BIM was not developed considering BPA. The description aligns with UOB 2.2 "*Optimise fabric and layout*" (see Figure 6.14).

1. The Sustainability Engineers received the Architectural model that contained walls, slabs, windows, and shading devices (LOD200).
2. They, then, had to rebuild the model in the BPA simulation software to estimate loads (i.e. heating and cooling), indoor environmental analysis (e.g. thermal, light, ventilation). Daylight performance was considered a critical aspect of design that should be assessed, as early as possible in the design process.

The Interviewee (Sustainability Engineer/BREEAM Assessor) recommended that a specialist member, within the Architectural design team, should be preparing separate specialised models for each discipline before sharing in the CDE. This way the delivered BIMs would be fit for purpose (in this case BPA).

6.3.16. Narrative 16: Iterative sustainability assessment process [Cyan UOBs]

Another Interviewee (CS14/Sustainability Engineer/BREEAM Assessor) described the sustainability assessment process of a commercial office building.

1. In the first instance, the Sustainability Engineers received a massing model LOD100 (UOB 2.1.1). Then, they assessed overshadowing and access to daylight (UOB 2.1.3), thermal performance (UOB 2.1.2) and photovoltaics' potential (i.e. solar analysis, UOB 2.1.5). Regulatory requirements and planning constraints were considered at this point before proceeding. For that

reason, extensive engagement with the Planning Consultant was required (Junction J4). See Figure 6.25 for the amended decomposition of UOB 2.1 "*Develop building massing*".

2. The Sustainability Engineers advised the Architect, MEP Engineer, and Structural Engineer regarding the advantages of implementing a steel frame instead of a concrete one. After that, they received the BIM (Revit LOD200) including geometry, U-Values, and G-Values (UOBs 2.2.1 and 2.2.2). See Figure 6.26 for the amended decomposition of UOB 2.2 "*Optimise fabric and layout".*
3. The Interviewee, then, attempted to import the BIM in IES-VE software to perform simulations for the following aspects: (i) daylight (UOB 2.4.8); (ii) HVAC performance, energy consumption, carbon emissions (UOB 2.4.1 decomposition); (iii) heating and cooling loads (UOB 2.4.6); (iv) alternative and renewable technologies, fabric (U-Values), shading devices (UOB 2.4.12, solar performance); and (v) regulatory compliance (Part L) (UOB 2.4.13). The Interviewee stated that *"it took a lot of analysis at this stage".* The interoperability problems started at this stage, since the geometry of the model was complex and was not compatible with IES-VE. The Interviewee suggested that they should only receive a simple geometric model that contained the properties of the materials. See Figure 6.27 for the amended decomposition of UOB 2.4 "*Develop holistic concept*".
4. Before the final Sustainability Strategy was signed-off, the BPA assessment report needed to be approved by the Client, the Architect, the MEP Engineers, and the Planning Consultant (Junction J16).

UOB 2.1.5 "*Perform solar analysis*" and UOB 2.4.13 "*Assess Part L compliance*" have been added to the IDEF3 model (see Figures 6.25 and 6.27 respectively). UOBs 2.1.3, 2.2.2, 2.2.5, 2.2.7, 2.4.9, and 2.4.12 have been renamed to reflect the content of the described tasks more accurately. Figures 6.25, 6.26, and 6.27 illustrate the changes to the decompositions of UOBs 2.1, 2.2, and 2.4.

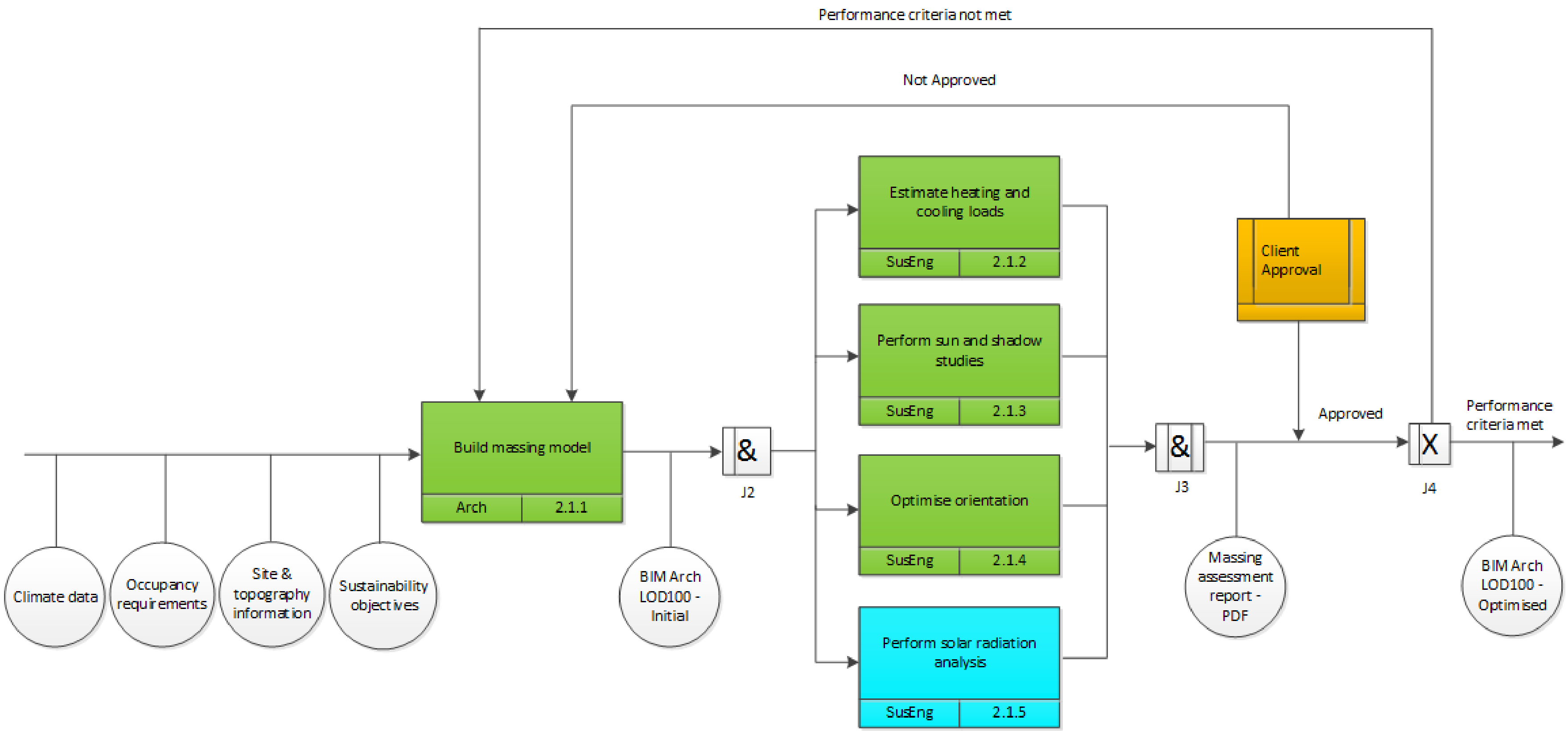


Figure 6.25 UOB 2.1 "Develop building massing" decomposition amended according to Narrative 16 [Cyan UOBs]

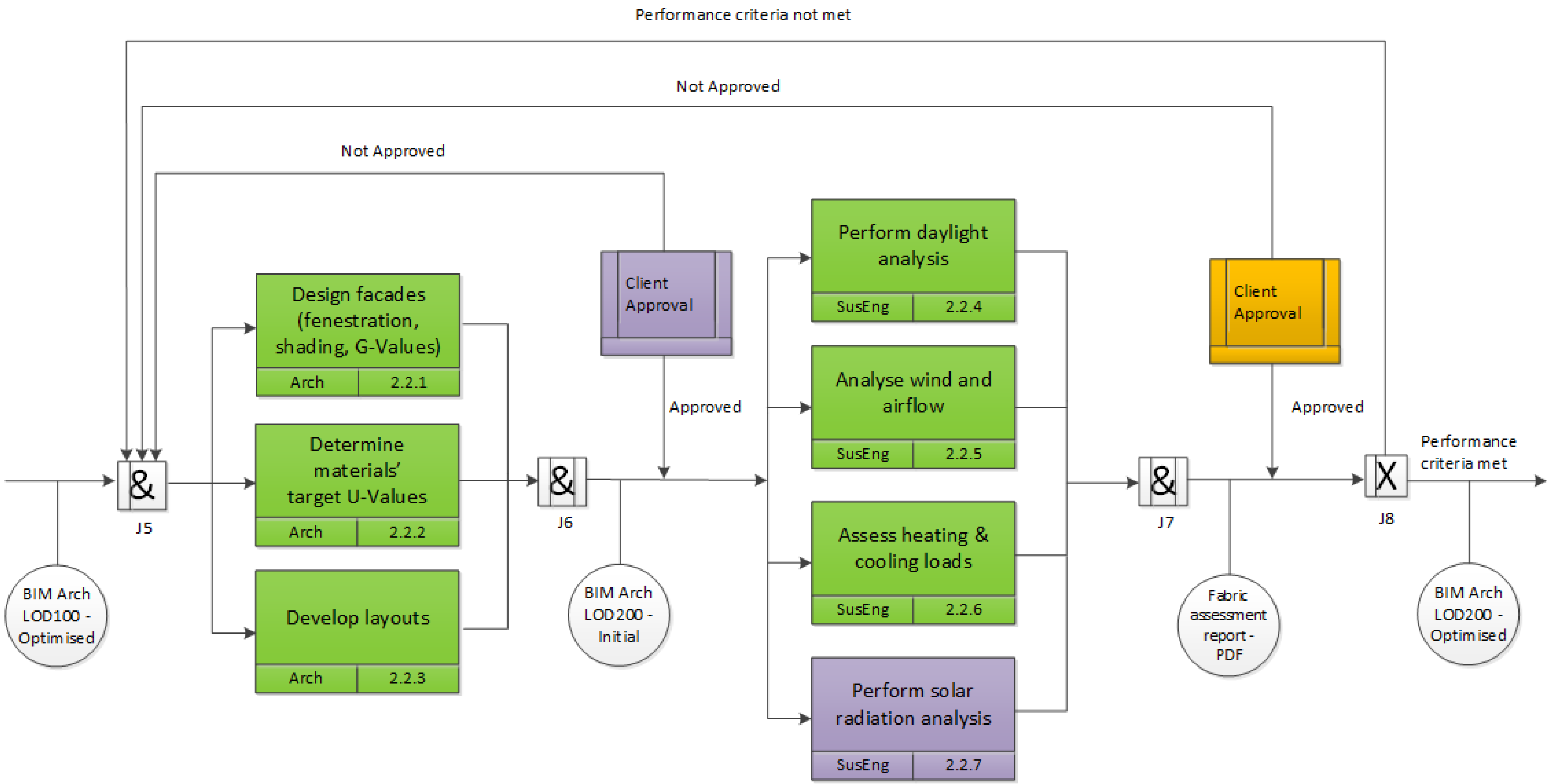


Figure 6.26 UOB 2.2 "Optimise fabric and layout" decomposition amended according to Narrative 16 [Renamed UOBs]

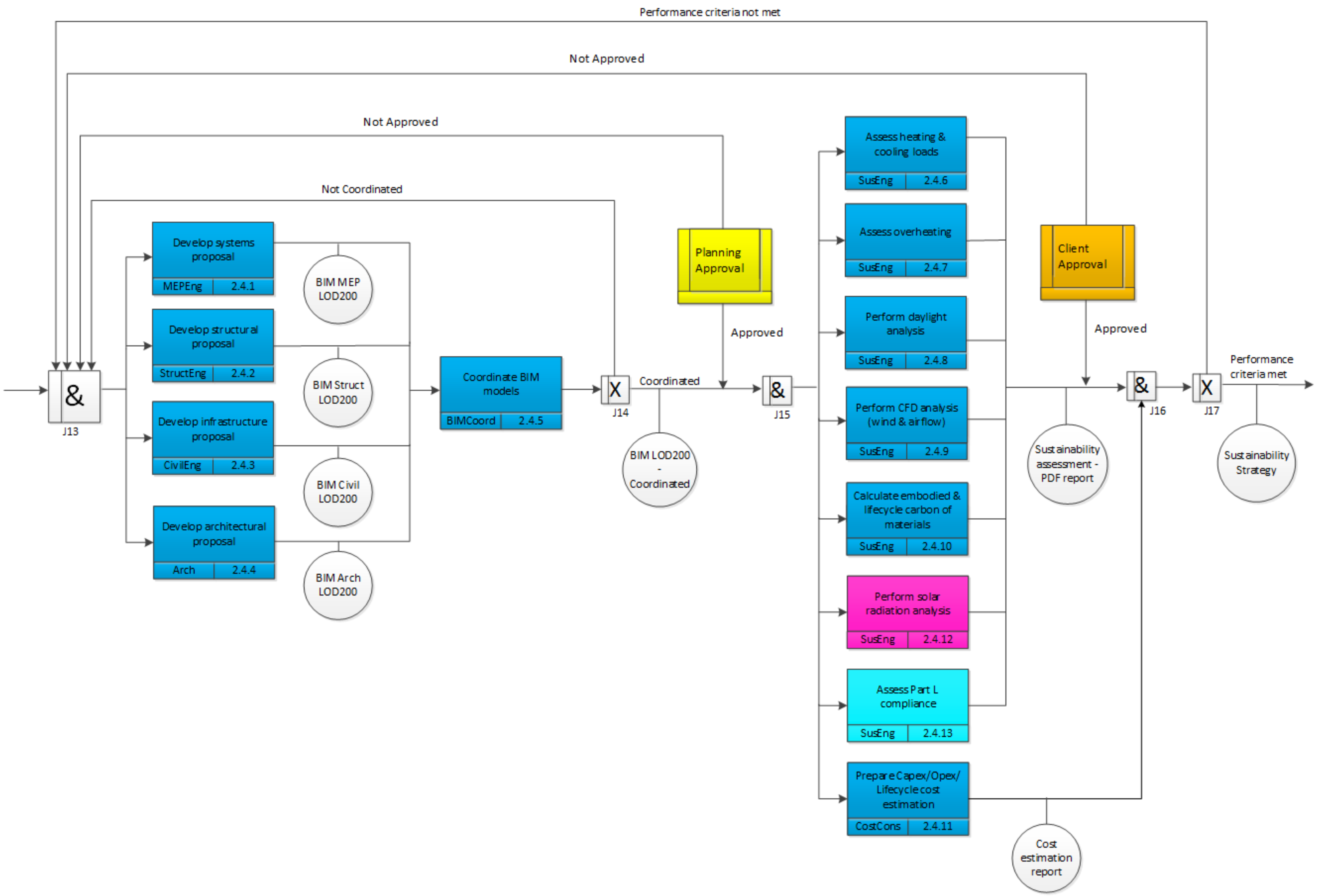


Figure 6.27 UOB 2.4 "Develop holistic concept" decomposition amended according to Narrative 16 [Cyan UOBs]

6.3.17. Narrative 17: BIM-enabled BPA from inception to completion of stage 2 [Brown UOBs]

An Interviewee (Sustainability Engineer/BREEAM Assessor) described the high-level process of BIM-enabled SBD. This description informs and validates UOBs 2, 2.1, 2.2, and 2.3 (see Figures 6.12, 6.25, 6.26, and 6.13 respectively).

1. The first task for the Sustainability Engineer was to perform a climate and weather analysis utilising IES-VE software. The inputs required were the climate data for the location of the site. The weather tool within the software, analyses the data and suggests the adequate environmental design strategies that can be implemented based on the climatic conditions. As a result, UOB 2.0 *"Perform climate and weather analysis"* has been added to UOB 2 "*Develop concept design*" decomposition diagram (see Figure 6.28).
2. These recommendations were shared with the Architect, who developed a massing model (UOB 2.1.1). Then, the Sustainability Engineer assessed the daylight availability and solar gains (UOB 2.1.3), and optimised the orientation and location of the building's mass on the site (UOB 2.1.4). Along with that, the target was to reduce energy demand by minimising the heating and cooling loads required to achieve thermal comfort inside the building (UOB 2.1.2).
3. The next stage was to further reduce energy demand by implementing passive design strategies (UOBs 2.2.1 to 2.2.3) while assessing their performance in IES-VE software (UOB 2.2.4 to 2.2.7). The outputs of this analysis were a report and a PowerPoint presentation that contained the interpretation of the numeric results of the BPA. The IES-VE model was not submitted though; only snapshots of the analysis were shared with the rest of the design team along with recommendations that explained the suggested design strategies.
4. The next stage was for the MEP Engineers to determine the energy sources (UOB 2.3.1) and the mechanical ventilation strategy, or justify the lack of it (UOB 2.3.3). The Sustainability Engineer collaborated with them to assess the energy consumption (UOB 2.3.6), carbon emissions (UOB 2.3.7), and compliance with Part L (UOB 2.3.8) utilising IES-VE software (see Figure 6.29).

5. This iterative process continued until the concept was optimised, and approved, by the Client, the Architect, the Sustainability Engineer, and the MEP Engineer (Junction J12).
6. Finally, a BREEAM (design stage) pre-assessment took place (Junction J17), and based on that the sustainability strategy was determined.

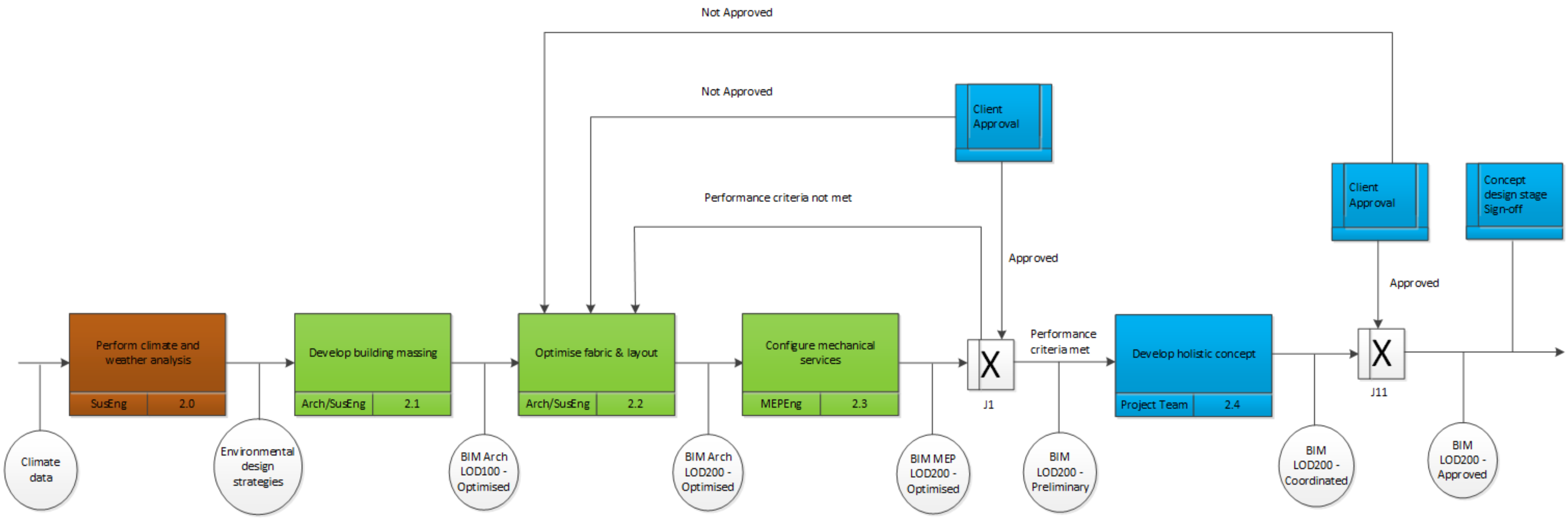


Figure 6.28 UOB 2 "Develop concept design" decomposition amended according to Narrative 17 [Brown UOBs]

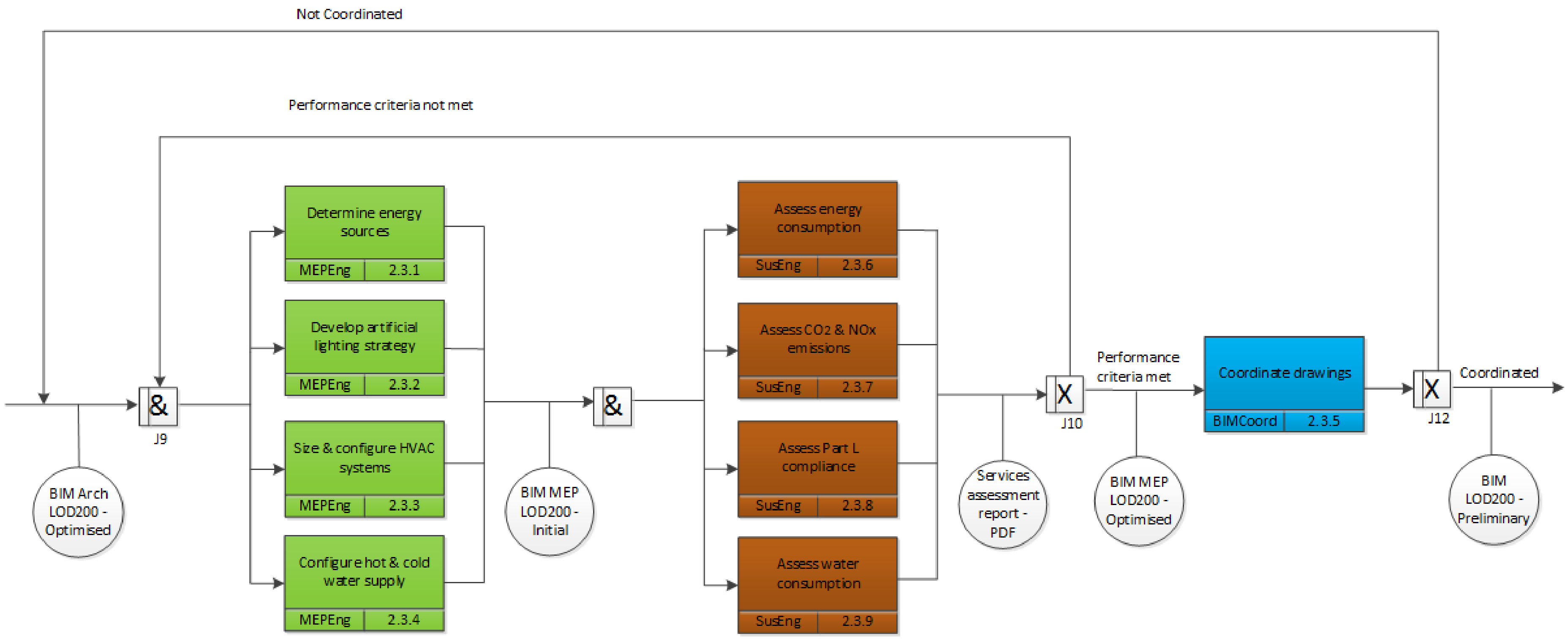


Figure 6.29 UOB 2.3 "Configure mechanical services" decomposition amended according to Narrative 17 [Brown UOBs]

6.3.18. Narrative 18: Collaboration within an integrated design practice

An Interviewee (Sustainability Leader of the MEP engineering team) described the SBD collaborative process within an integrated design practice. This Narrative validates, and informs, the UOB 2 "*Develop concept design*" decomposition (see Figure 6.28).

1. The briefing requirements that the sustainability specialists received from the Client included spaces, functions, key sustainability targets and metrics, renewable energy aspirations, and sustainability rating requirements (e.g. BREEAM).
2. The information that they received, from the rest of the design team, was a skeleton of the Architectural design (windows, doors, voids, volumes) and the Structural design (building frame). The format of the information exchanged was 2D drawings, 3D models, and *"true BIM models"*.
3. The sustainability goals that they prioritised were the embodied carbon of materials, and the carbon emissions of mechanical services (performed in IES-VE software). The outputs of the BPA assessment were a formal report, and a presentation to share the results with the rest of the design team.
4. Finally, they performed a BREEAM pre-assessment to determine the targeted credits.

6.3.19. Narrative 19: Architect's and Sustainability Engineer's viewpoints combined

The Sustainability Engineer and Architect of Case Study 9 (CS9) reported the same incident from both perspectives, enriching the Narrative. This incident aligns with UOB 2.2 "*Optimise fabric and layout*" decomposition (see Figure 6.26).

1. The Client's sustainability aspiration was to achieve "*holistic sustainability*". Therefore, the objectives of the design team were to maximise daylight and natural ventilation, venting and cooling, passive heating, flexibility, and disabled access. Furthermore, the certification's rating requirement was BREEAM Excellent, which was achieved.
2. The design strategies selected by the design team were the following: (i) material re-use, (ii) innovative technologies, (iii) solar tubes, (iv) spatial

thermal mass boarding, (v) solar-control glass, (vi) low energy fitments, (vii) local sensors, (viii) gas and biomass boilers, and (ix) rainwater harvesting. Emphasis was given on the performance targets for daylighting (lux levels).

3. An iterative process of design development and performance assessment took place to minimise overheating. The initial design was developed based on rules of thumb (by the Architect). The Sustainability Engineer, then, modelled the building in EDSL TAS software to determine the airflows within the spaces. The Sustainability Engineer collaborated closely with the Architect, suggesting changes to the location of the windows. The Interviewees claimed that the most significant design decisions were the following: (i) orientation, (ii) the layout of rooms, and (iii) the solar shading (passive design was prioritised).
4. Then, the MEP Engineers provided the specifications of services, and the Quantity Surveyor assessed the cost of the building elements.
5. Finally, the Architect provided the design team with 2D drawings of floor plans and elevations. In addition, the Sustainability Engineer shared a report containing the thermal simulation's results, and snapshots of their BPA model.

6.3.20. Narrative 20: Implementing SBD in a Level 2 BIM maturity project

An Architect (CS10) reported his perspective while working within a Level 2 BIM maturity project, implementing SBD. The site constraints were the lack of space, and the west dominant orientation. This Narrative aligns with UOB 2.1 "*Develop building massing*" and UOB 2.2 "*Optimise fabric and layout*" (see Figures 6.25 and 6.26 respectively).

1. The Architects authored their BIM, in Revit (LOD200), and shared it with the rest of the design team (UOB 2.2). Autodesk BIM 360 Glue was utilised for collaboration although workshops were the main method of communication.
2. BPA (at early stages), occurred internally, utilising Trimble Sefaira software to assess building form, orientation, and shading. The Interviewee emphatically stated the following: *"that instant feedback is really useful"*. Furthermore,

sensitivity analysis was performed to adjust the orientation of the building so as to achieve the minimum heating and cooling loads (UOBs 2.1 and 2.2).

3. The critical decisions, for sustainability, were the following, according to the expert: (i) building orientation; (ii) location and shape of windows, and amount of glazing; (iii) power sources; and (iv) heating and cooling loads. As a result, the Sustainability Engineers shared a report to give advice to the rest of the design team's members. A *"giant checklist"* was also used to track the progress of sustainability considerations.
4. As soon as the Sustainability Engineers received the Structural and MEP BIMs, they assessed the environmental performance utilising a dynamic simulation BPA software tool. The iterative process followed a weekly cycle until the performance was optimised. The Interviewee claimed that *"it is easier if everyone is using Revit".*
5. The final BIM LOD200, for concept design, contained floorplates, internal walls, external walls, and target U-Values, but no detailed specifications for building materials.

6.3.21. Additions to the model [White UOBs]

Once the BIM-enabled uses, and their interdependencies, were identified, several functions were added to the IDEF3 model, based on unstructured descriptions, and literature review findings (see Chapter 5). The tasks' relationships have followed the logical patterns (design-assessment iterations), which have been identified from the incidents' narratives.

Thus, the decomposition of UOB 2.4 "*Develop holistic concept*" has been amended considering the input of several Interviewees (Sustainability Engineers and BREEAM Assessors). As a result, the sustainability considerations that are relevant to each discipline (MEP Engineer, Structural Engineer, Civil Engineer, and Architect) have been included in the decompositions of UOBs 2.4.1, 2.4.2, 2.4.3, and 2.4.4 (see Figures 6.30 to 6.33). Furthermore, the types of BPA that are assessed holistically remain in the high-level decomposition of UOB 2.4 "*Develop holistic concept*". UOB 2.4.6 "*Test for robustness*" has been added to the model based on Narrative 5, by the

Architect of CS3. UOB 2.4.8 "*Perform BREEAM Pre-assessment*" is added to the model based on Narrative 11 a BREEAM Assessor/Sustainability Engineer (see Figure 6.30). UOB 2.2.10 "*Perform acoustic analysis*" has been added to the model based on unstructured interview descriptions from Sustainability Engineers and Architects (see Figure 6.34). The amendments to the model are shown below in Figures 6.30 to 6.34.

The complete version of the process model (before the final validation and refinement) can be found in Appendix D.

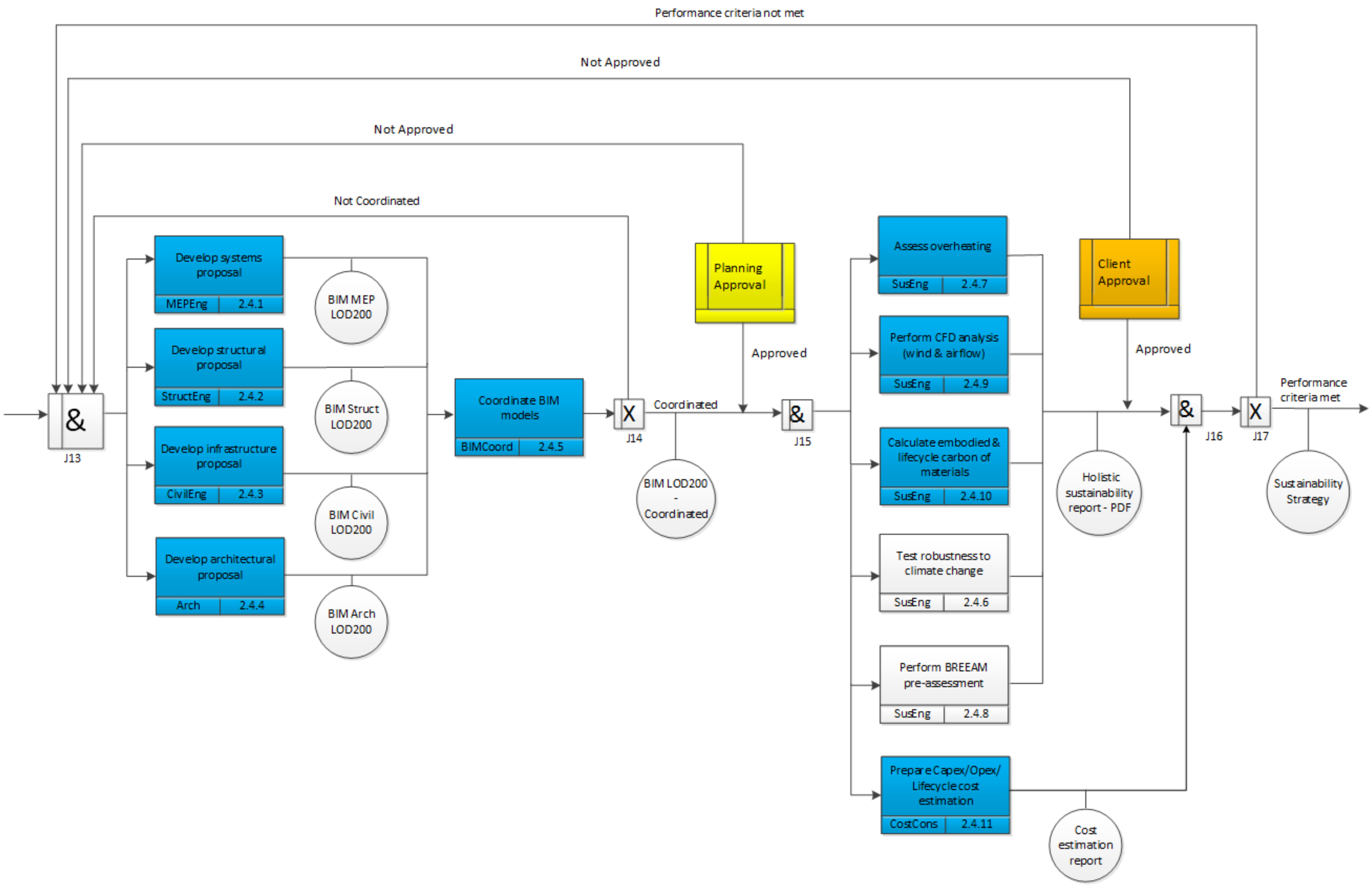


Figure 6.30 Amendments to UOB 2.4 "Develop holistic concept" decomposition based on unstructured descriptions [White UOBs]

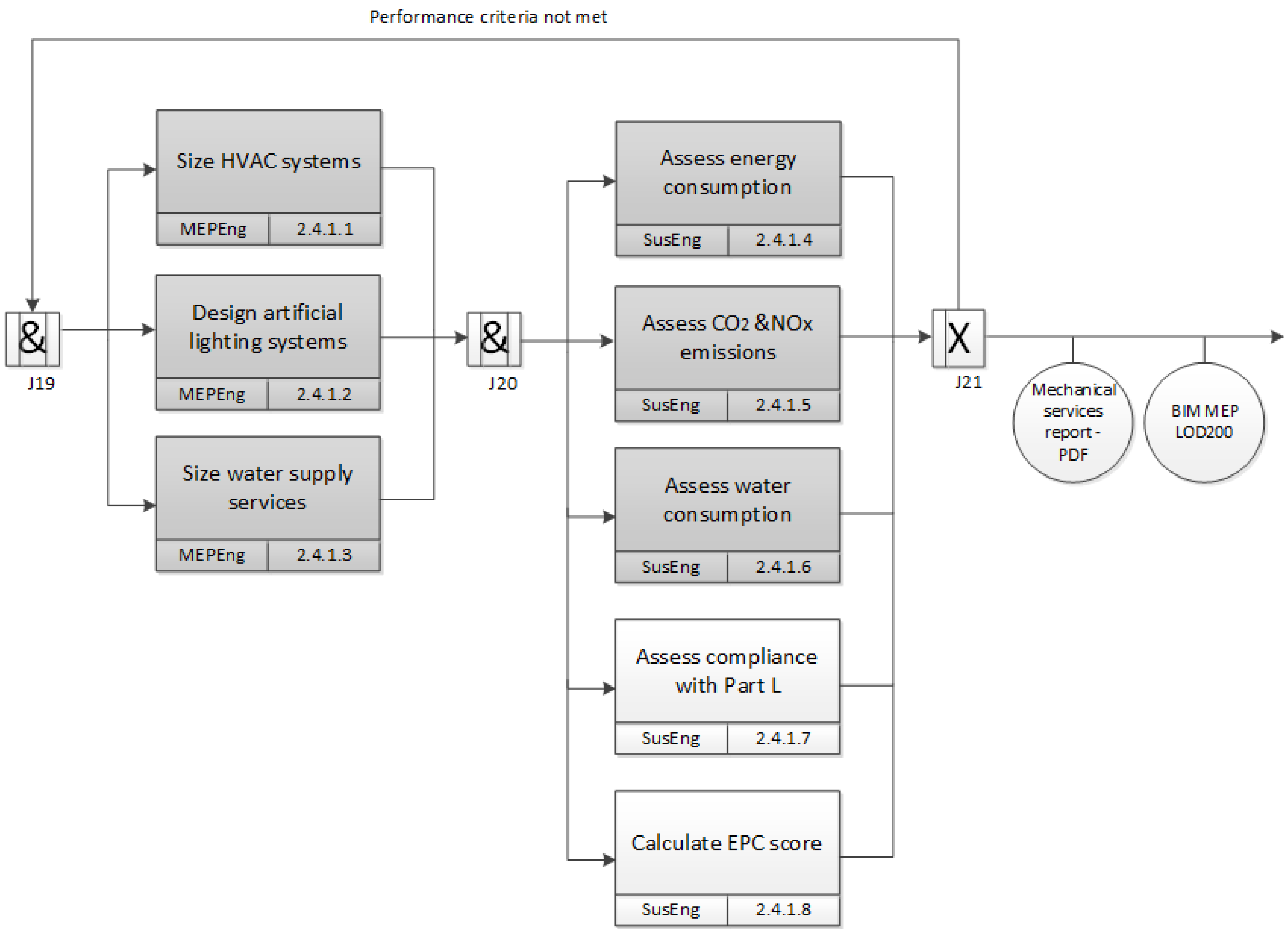


Figure 6.31 Amendments to UOB 2.4.1 “Develop systems proposal” based on unstructured descriptions [White UOBs]

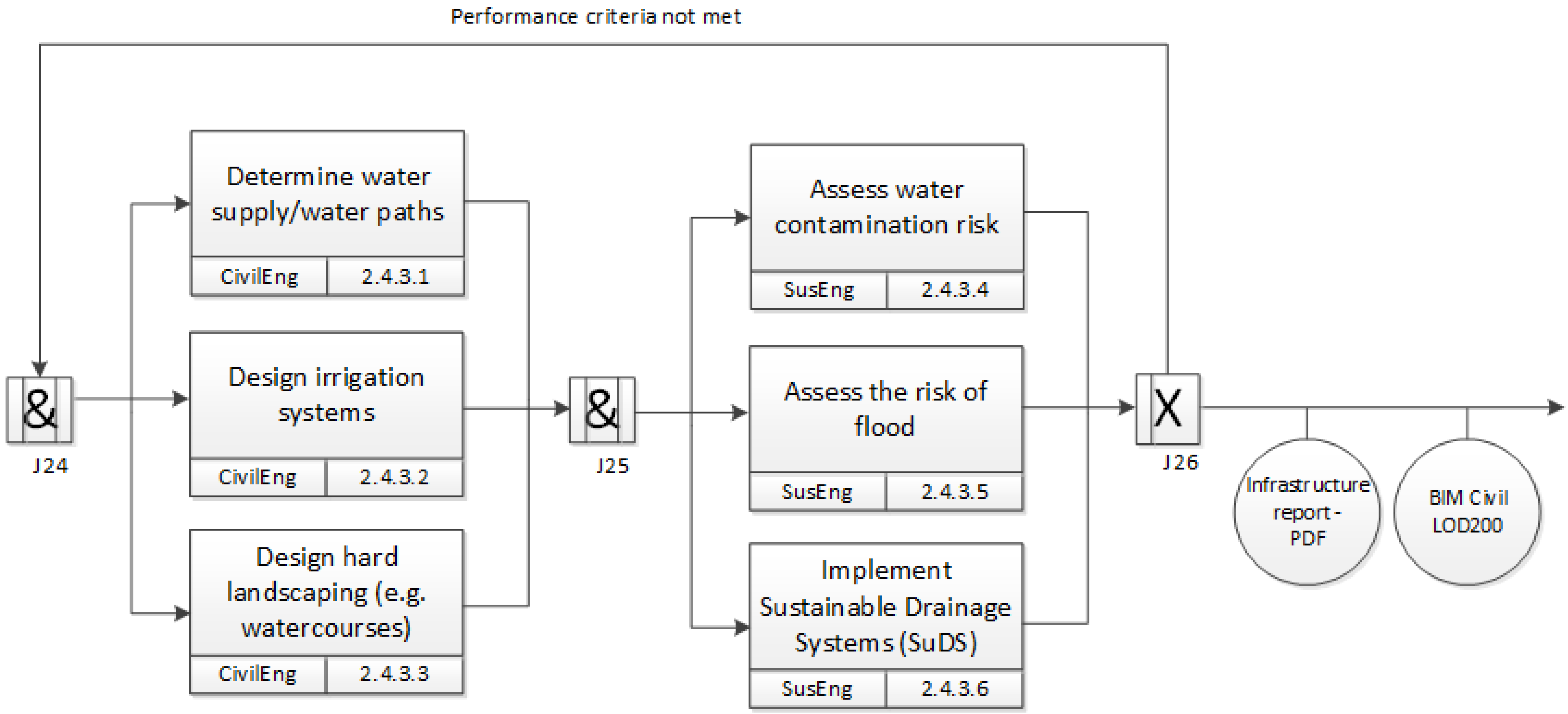


Figure 6.32 UOB 2.4.3 "Develop infrastructure proposal" created based on unstructured descriptions [White UOBs]

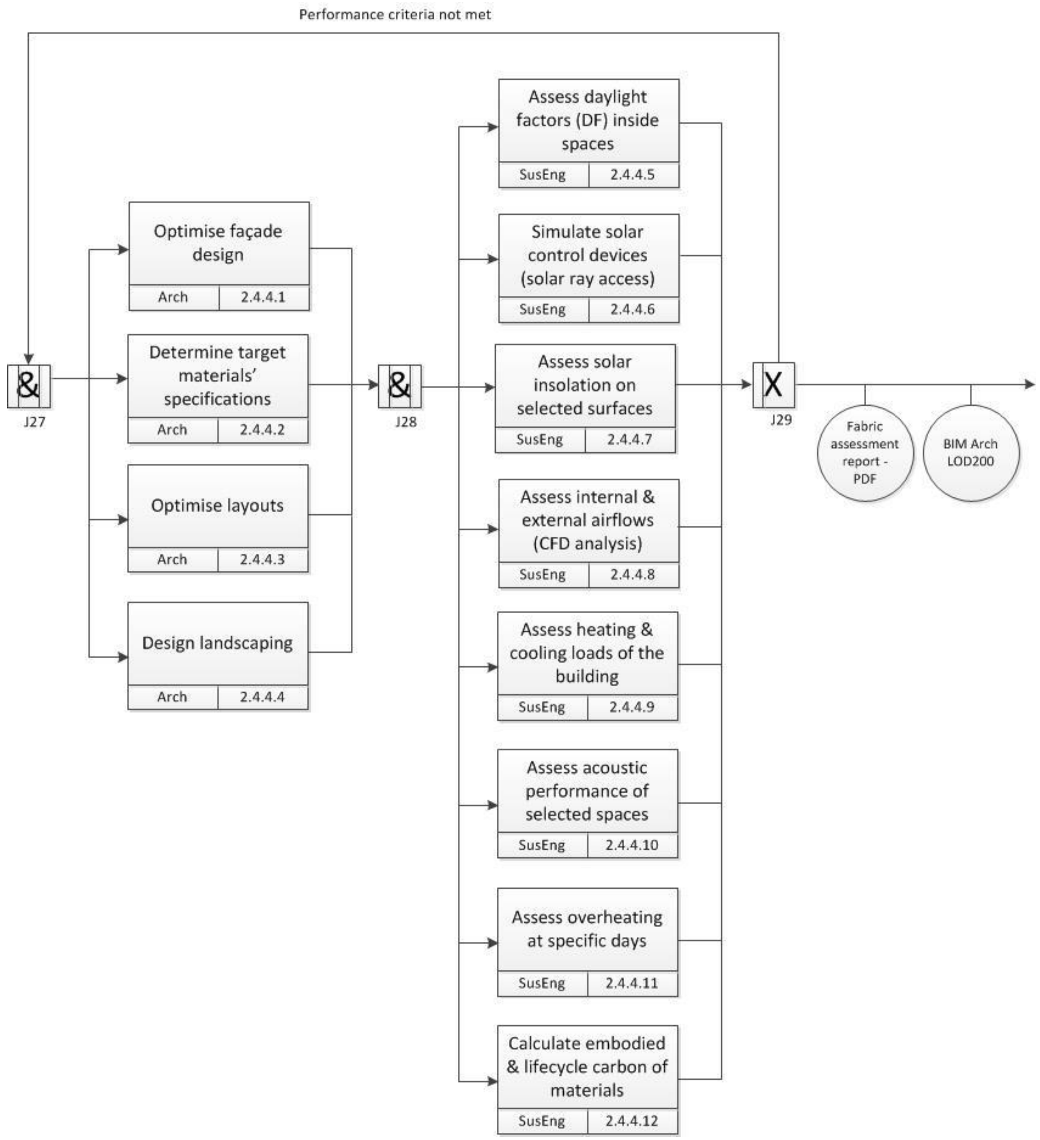


Figure 6.33 UOB 2.4.4 "Develop architectural proposal" created based on unstructured descriptions [White UOBs]

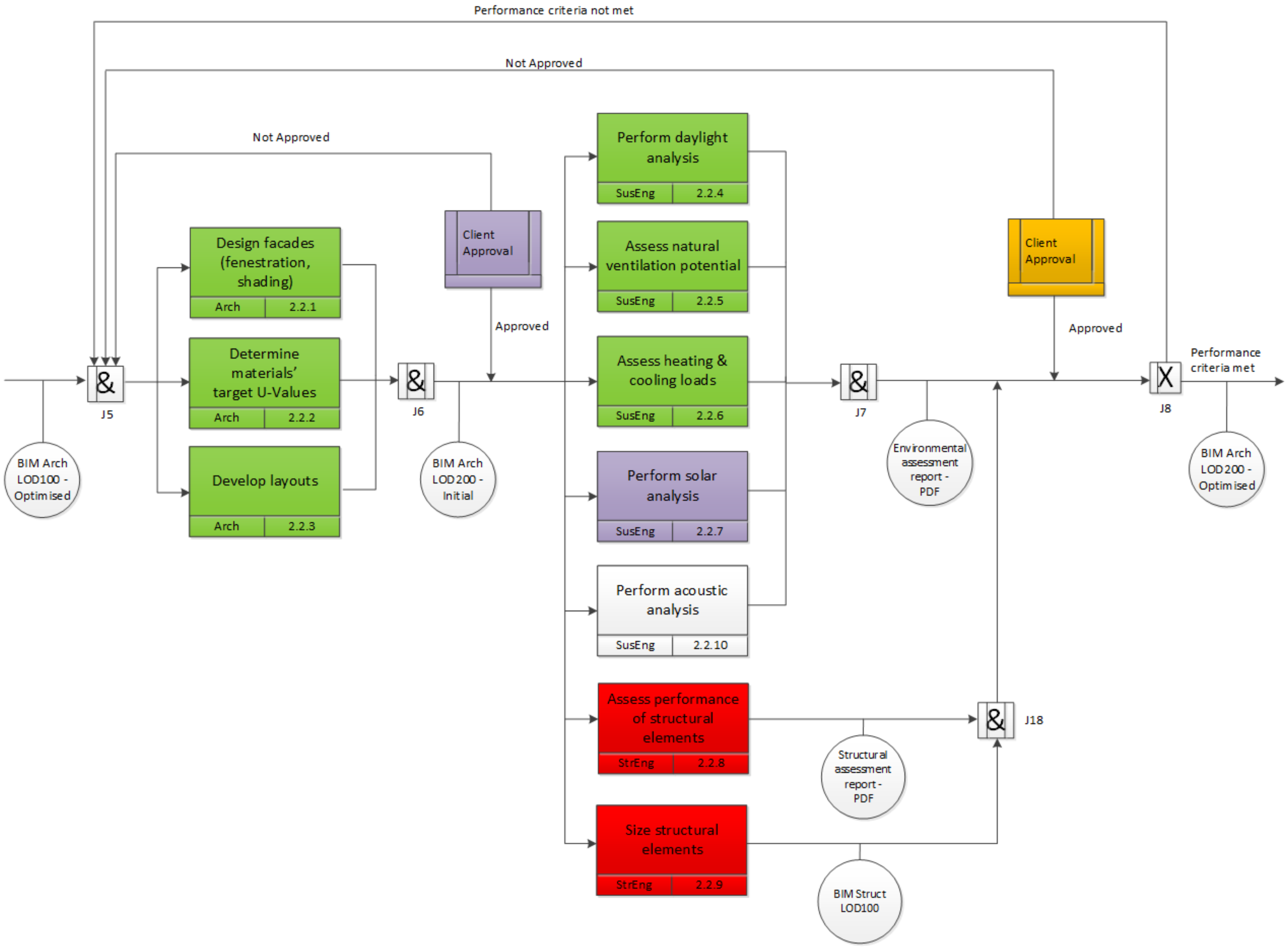


Figure 6.34 UOB 2.2 "Optimise fabric and layout" amendments based on unstructured descriptions [White UOBs]

6.4. Green BIM Box (GBB): ontology and operation

This section aims to define the ontology of the prototype application, developed in this research, so as to provide an understanding of its structure and schematics (Uschold and Gruninger, 1996). Green BIM Box (GBB) is a conceptual workflow management prototype tool that formalises design goals, roles, responsibilities, methods, and deliverables coordinating them into a common process holistically based on the lessons learnt from the best practices (discussed in Chapters 5 and 6). GBB aims to enable a shift from the traditional linear collaboration SBD process into a concurrent one, where the design is developed and assessed at the same time, during Work In Progress (WIP). Chapters 5 and 6 have discussed that informal and unregulated communication channels and collaboration patterns are the current norm for SBD, which require a wide range of specialist subcontractors' involvement. This practice has proven to lead to design rework, project delays, and additional costs to achieve sustainable outcomes.

First, the content of the three layers of the system (presentation, service, and data and knowledge layer), which facilitate the implementation of the IDEF3 process model, is explained. Then, the interplay between the three layers (the execution of a structured multidisciplinary SBD process), and the human-computer interactions and automated tasks, are described through Use Case Scenarios utilising Sequence Diagrams (OMG UML notation, discussed in Section 4.6.3). Zachman's framework (2006) has provided a guide to the schematics of enterprise ontology architecture. Figure 6.35 is a simplified diagram of a physical architecture of the prototype application at a high level. The three-layer system design (Buschmann et al., 1996; Microsoft, 2015) consists of: (i) the Presentation layer, (ii) the Service layer, and (iii) the Data and Knowledge Access layer. The Presentation layer is the User Interface (UI) of the application, which is web-based utilising a web browser (e.g. MS Internet Explorer, Google Chrome, Mozilla Firefox). Furthermore, plug-in applications for discipline specific applications are considered (e.g. Revit, IES-VE) in order to facilitate the multiple perspectives that are required. The Service layer is located in a web server so as to coordinate the top and bottom layers by containing the logical decisions and the commands of the application. Its role also includes moving the processed data between them. In this scenario, the middle layer contains the IDEF3 process model with the workflows, which are the rules of the developed system. These functions include management, team support, access codes, system's rules, and data mapping. Query management, document management, approval, messaging, and quality management are its main functionalities (Wilkinson, 2005). The Data and Knowledge Access layer consists of one or more databases (e.g. CDE) where the Graphical (e.g. individual models, and federated model) and the Non-graphical information (e.g. documents, and specifications) are stored. Foundation services can be used by all three layers (Microsoft, 2015); those include Security and Communication (e.g. asynchronous messaging) layers. Screenshots of the Presentation layer (GBB mock-up), and an illustration of the Data and Knowledge Access layer (Entity Relationship Diagram, ERD) (Chen, 1976) can be found in Appendix D.

The behaviour of the system is demonstrated in the following sub-Sections utilising Use Case Scenarios. A Use Case is defined as: *"a concrete description of activity that the user engages in when performing a specific task, description sufficiently detailed so that design implications can be inferred and reasoned about"* (Carroll, 1995). These five Scenarios are based on the Level 2 process decompositions of the IDEF3 model, which have been discussed in Section 6.3 in detail. The complete process model can be found in Appendix D, and the validated, and final, version is discussed in Chapter 7. The developed diagrams establish the links between the three layers of the system's architecture, and show the interplay among the users and automated functions.

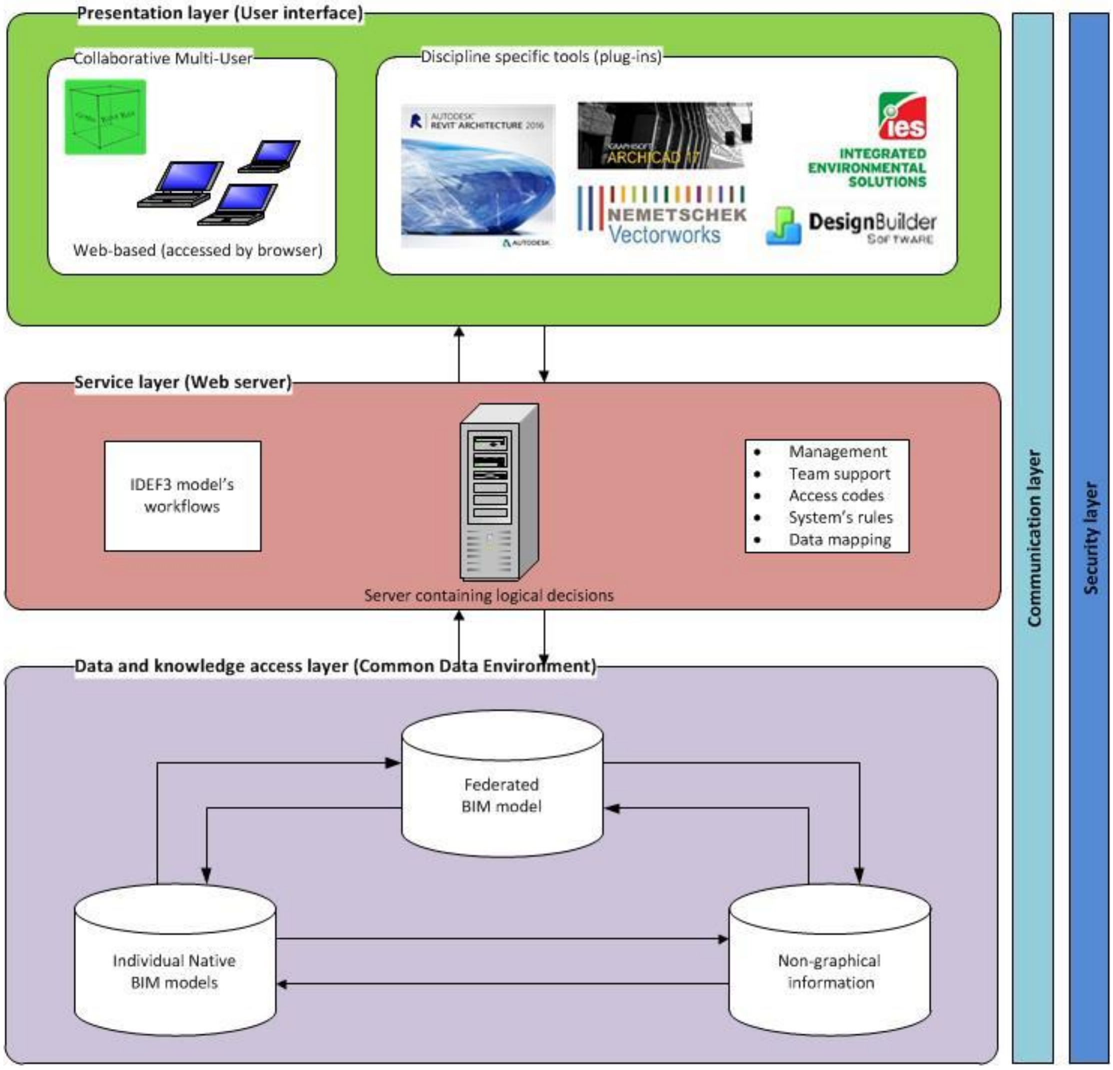


Figure 6.35 Green BIM Box – three-layered system architecture

6.4.1. Use Case Scenario 1: Strategic Definition and Briefing [UOBs 0 and 1]

The 1st Use Case Scenario presents the general principle of the behaviour of the system during Strategic Definition (RIBA stage 0) and Briefing (RIBA stage 1). The administrator of the organisational SBD process may vary, depending on the procurement route, or the Client's experience. This role may be undertaken by the Client, Contractor, Design Lead, or Project Manager. In the example illustrated in Figure 6.36 the Project Manager is the administrator of the process. Utilising the web browser accessed application, the administrator selects the Client's requirements in the system. These are stored in the Service layer and a confirmation is sent to the Sender automatically (synchronous message). Furthermore, the Service layer automatically sends asynchronous messages to the stakeholders that have been assigned tasks, which describe the scope and the deliverables of each. A prerequisite of this task is that the design team members have discussed, and agreed the requirements amongst themselves, before the delegated tasks are finalised. The assumption is that the scope and deliverables of the tasks may be amended by the administrator of the system.

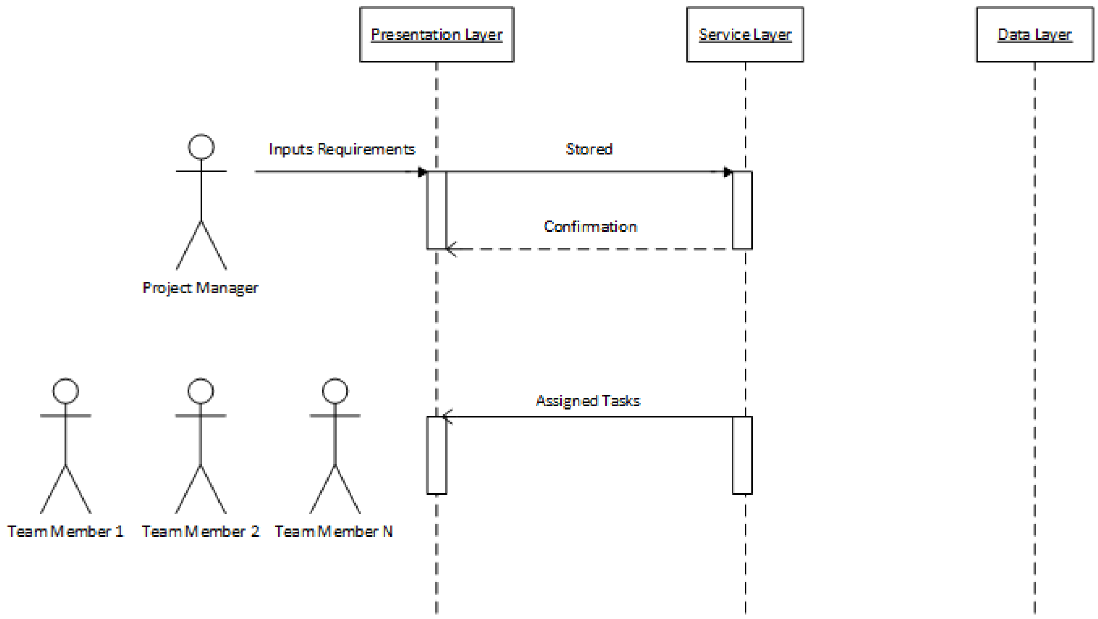


Figure 6.36 Use Case Scenario 1 – Strategic Definition and Briefing [UOBs 0 and 1]

6.4.2. Use Case Scenario 2: Building Massing [UOB 2.1]

The description of the 2nd Use Case Scenario, shown in Figure 6.37, corresponds to UOB 2.1 "*Develop building massing*" of the IDEF3 process model. Once the Architect completes UOB 2.1.1 "*Build massing model*", they upload the BIM Arch LOD100, either utilising the plug-in application, or through the web browser based application. The system audits the task (prompts for correct naming according to BS 1192:2007 (BSI, 2007) and counts – latest version ensured). The BIM file is stored in the Data and Knowledge Access layer and the Architect receives a confirmation that the process has been completed successfully. Then, the system automatically sends notifications to the stakeholders that have requested, and are authorized, to have an overview of the process (in this example, the Project Manager). Furthermore, the system prompts action from the Sustainability Engineer (to a set deadline). These asynchronous messages do not require immediate responses from the Receivers. Once the Sustainability Engineer, performs their assigned tasks (UOB 2.1.2 to 2.1.5), they upload the file/s (e.g. massing assessment report) to the system, following a similar process like the Architect (plug-in or web browser-based app). The system automatically notifies the stakeholders that have requested progress notifications (e.g. Project Manager) along with the ones that are required to take action (e.g. Client). Once the Client has reviewed the files, uploaded by the Architect and the Sustainability Engineer, they either Approve or Not Approve (accept or deny) the results, based on performance criteria or personal aesthetics. In case the outcomes of the tasks are Not Approved by the Client (or the responsible stakeholder), a loop is created, and the process iterates at the beginning. As soon as the outcomes are approved, all stakeholders that have participated in the process (Architect, Sustainability Engineer, and Project Manager) are notified that the task (UOB 2.1) has been completed, and they are prompted to start the next assigned task (UOB 2.2).

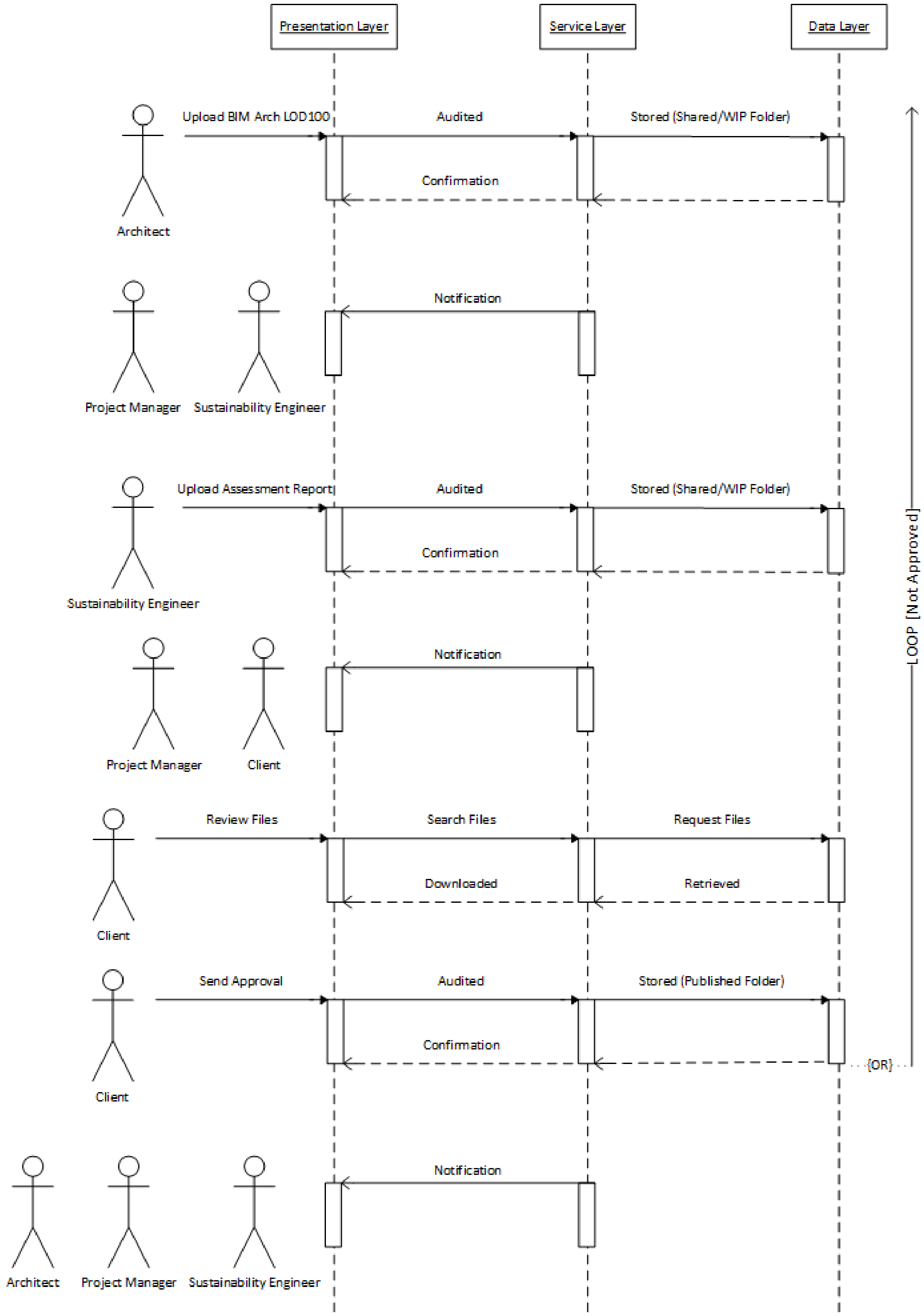


Figure 6.37 Use Case Scenario 2 - Building Massing [UOB 2.1]

6.4.3. Use Case Scenario 3: Building Fabric [UOB 2.2]

Figure 6.38 illustrates the sequencing of actions (Phases 1-3) during the implementation of UOB 2.2 "*Optimise fabric and layout*" (3rd Use Case Scenario). Phase 1 is described in Figure 6.39; the Architect completes UOBs 2.2.1, 2.2.2, and 2.2.3 and uploads the BIM Arch LOD100 following the same process as above (Section 6.4.2). According to the IDEF3 process, the Client approves (or not) the architectural design, and the system notifies the Architect accordingly. Once the architectural design is approved, the system notifies the Sustainability Engineer and Structural Engineer with asynchronous messages in order to trigger their tasks. These messages create two parallel threads (see Figure 6.38, 2a and 2b), so that the processes described in Figures 6.40 and 6.41 occur concurrently. During Phase 2a, the Structural Engineer performs the tasks assigned to them (UOB 2.2.8 and UOB 2.2.9) and uploads their model (BIM Struct LOD100) and the Structural Assessment report into the system. The Client reviews the results and either Approves the outcome, or Not, creating a loop in the process. Once the results are Approved, the stakeholders are notified to proceed to the next assigned task (including a set deadline). In the meantime, the Sustainability Engineer follows a similar process (Phase 2b). Once they perform their assigned tasks (UOB 2.2.4 to 2.2.10), the Project Manager and Client are notified regarding this update. The Client is, then, prompted to review the outcome of the analysis (Environmental Assessment report), and then, sends a response through the system. When the results have been Approved, the Sustainability Engineer is notified. Phase 3 (see Figure 6.42) includes automated asynchronous messages (as notifications) sent to the Project Manager, who has the overview of the process, and to the MEP Engineer so as to take action and initiate UOB 2.3 "*Configure mechanical services*".

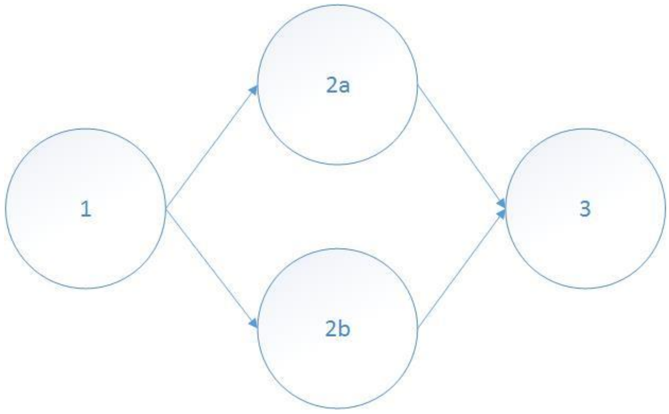


Figure 6.38 Sequencing of UOB 2.2 UMLs (Phases 1-3)

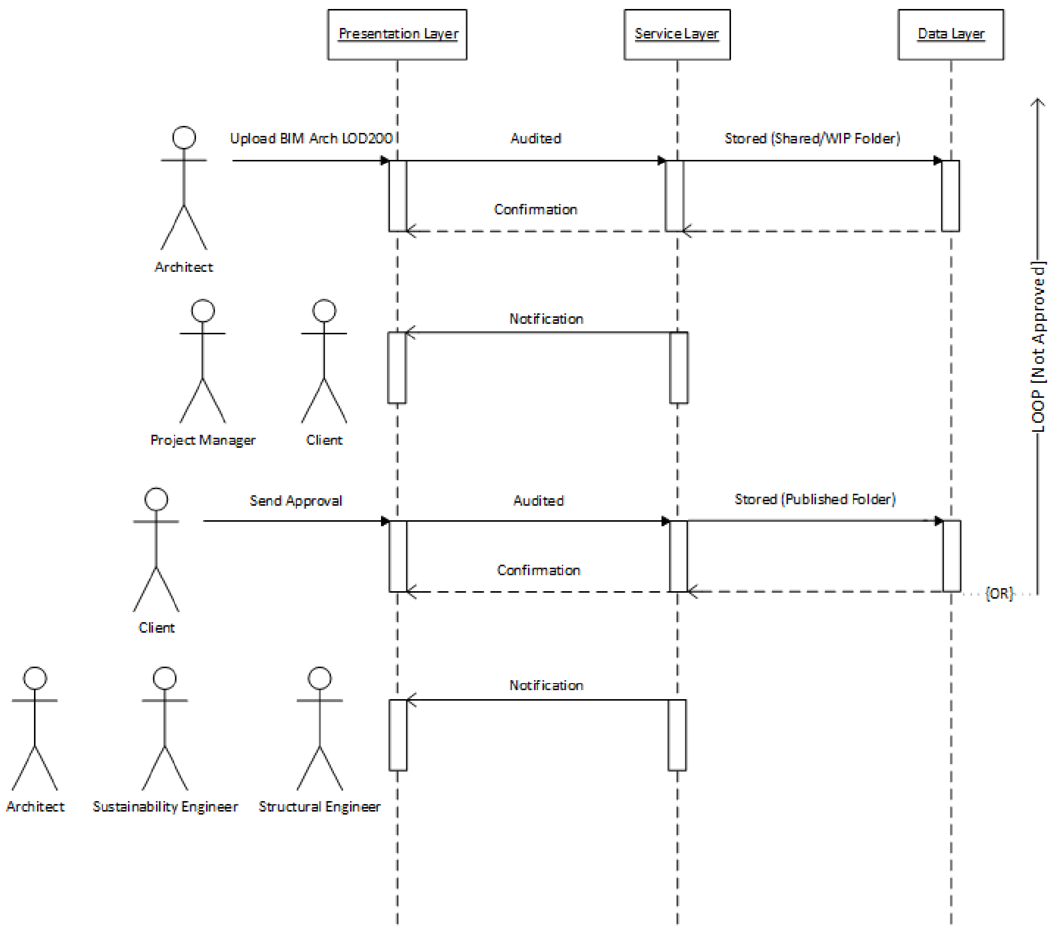


Figure 6.39 Use Case Scenario 3 – Building Fabric [UOB 2.2] (Phase 1)

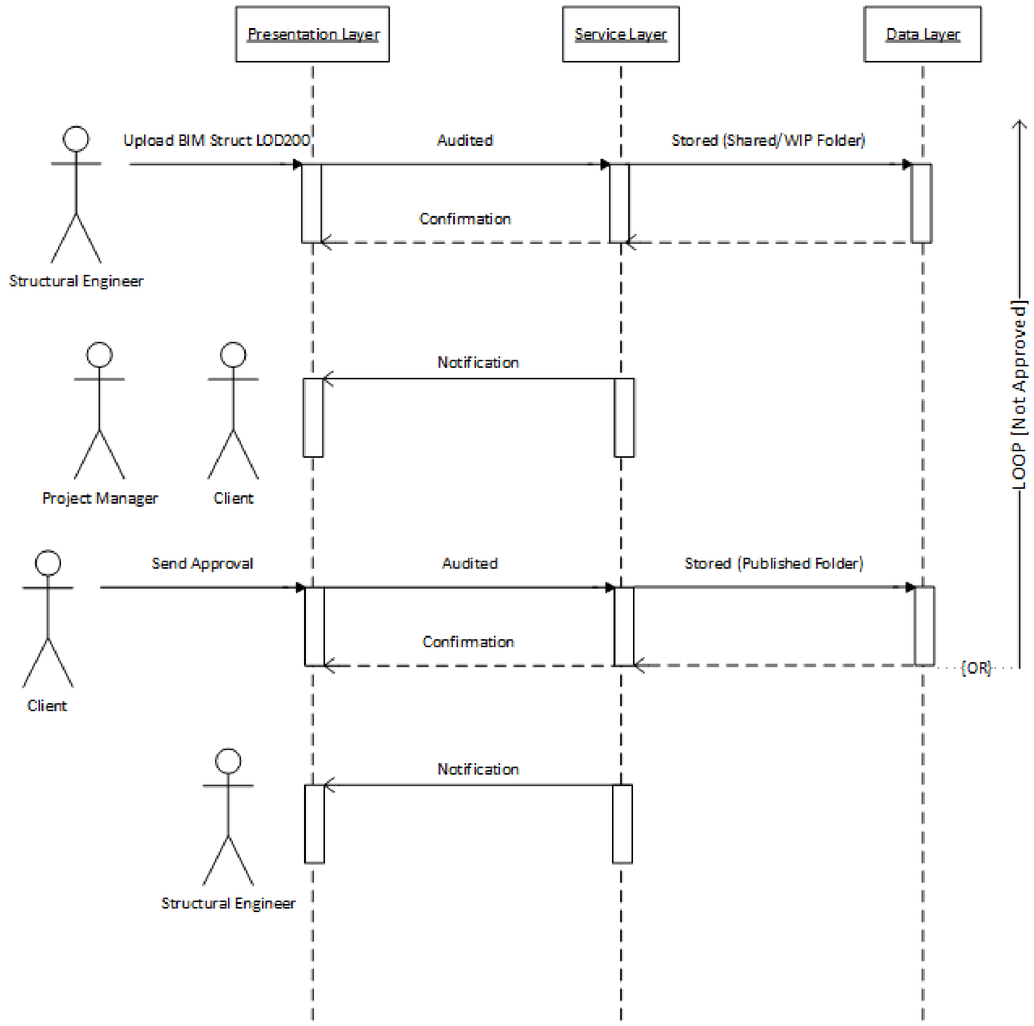


Figure 6.40 Use Case Scenario 3 - Building Fabric [UOB 2.2] (Phase 2a)

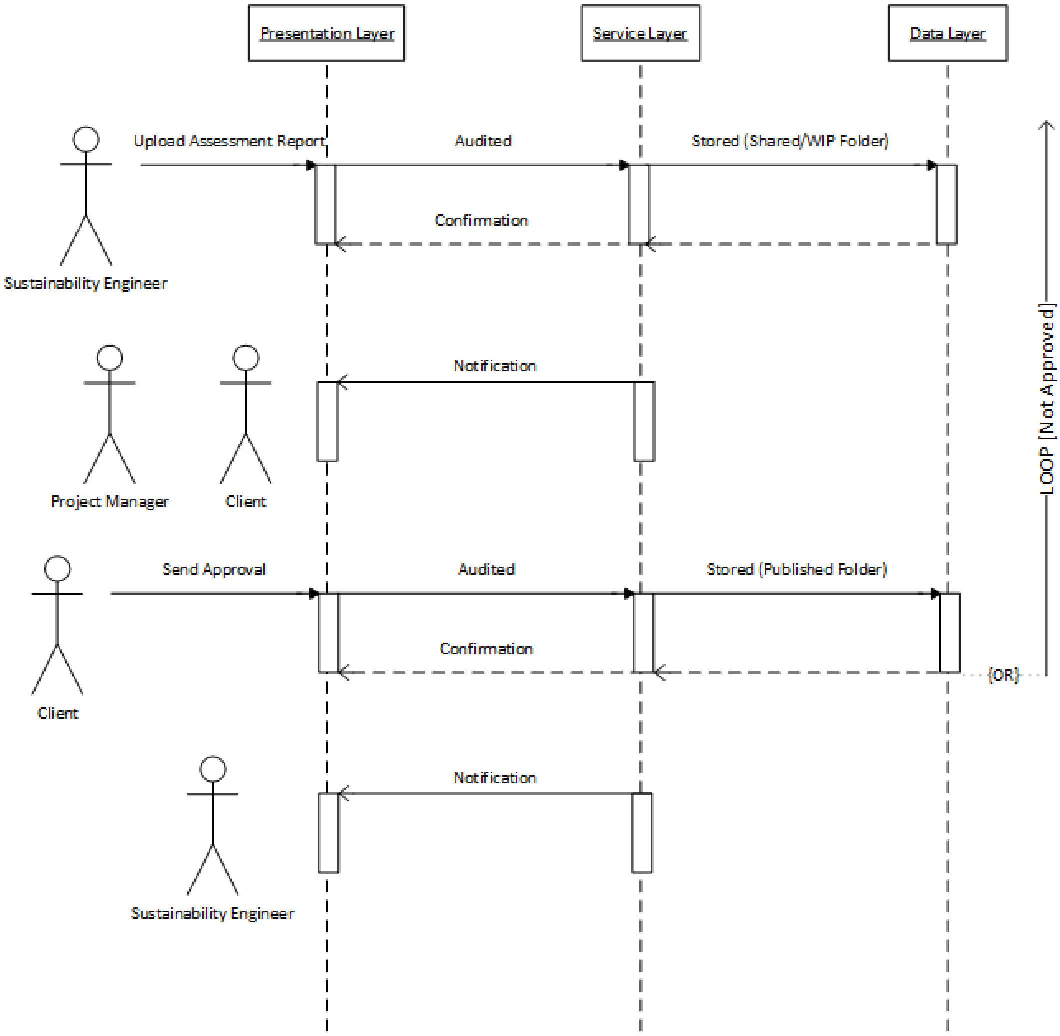


Figure 6.41 Use Case Scenario 3 - Building Fabric [UOB 2.2] (Phase 2b)

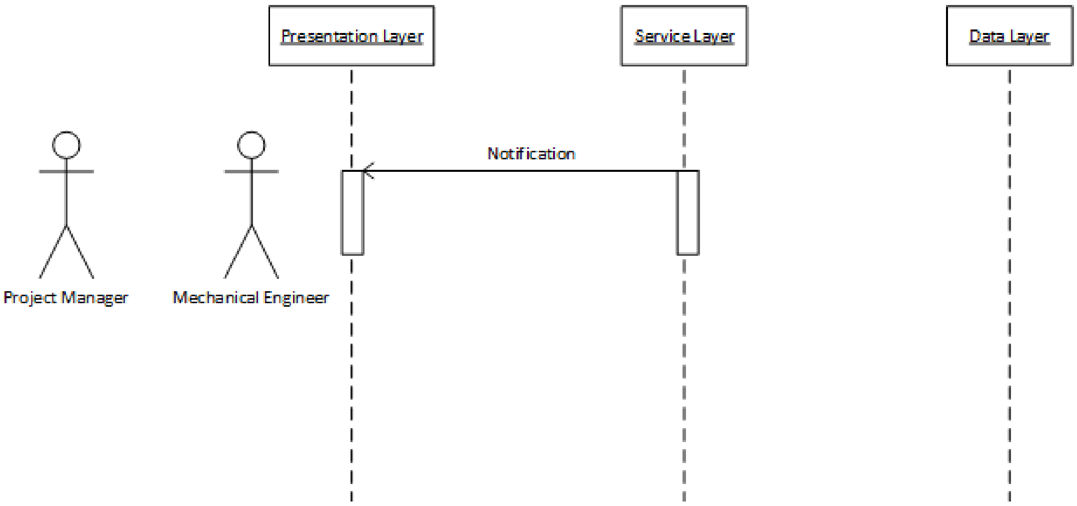


Figure 6.42 Use Case Scenario 3 - Building Fabric [UOB 2.2] (Phase 3)

6.4.4. Use Case Scenario 4: Mechanical Services [UOB 2.3]

The 4th Use Case Scenario describes the execution of UOB 2.3 "*Configure mechanical services*", from Phase 1 to Phase 2, illustrated in Figures 6.43 and 6.44 respectively. The MEP Engineer initiates the process by uploading the BIM MEP LOD200, after completing their assigned tasks (UOB 2.3.1 to UOB 2.3.4). The system audits the action and stores the file/s in the Database and Knowledge Access layer. Shortly after, the MEP Engineer receives a confirmation that the upload has been successfully completed (synchronous message). Then, the Project Manager (overview) and Sustainability Engineer (prompt) receive customised notifications. The Sustainability Engineer performs their assigned tasks (UOBs 2.3.6 to 2.3.9) and uploads the outputs (e.g. Services Assessment report) into the system. This action is audited in the Service layer, the file is stored in the Database and Knowledge Access layer, and a confirmation is sent synchronously. Then, the system automatically sends an asynchronous message (notification prompt) to the BIM Coordinator to initiate UOB 2.3.5. After the BIM Coordinator completes their task, notifications are sent to the responsible stakeholders. As soon as the set Criteria are met, and the Client approves of the design outcome (double condition iteration loop), the system proceeds to Phase 2. This entails sending automatic notifications (as messages) to each of the stakeholders prompting them to perform their delegated duties (UOB 2.4 assigned tasks), following the IDEF3 process model's structure (Service layer).

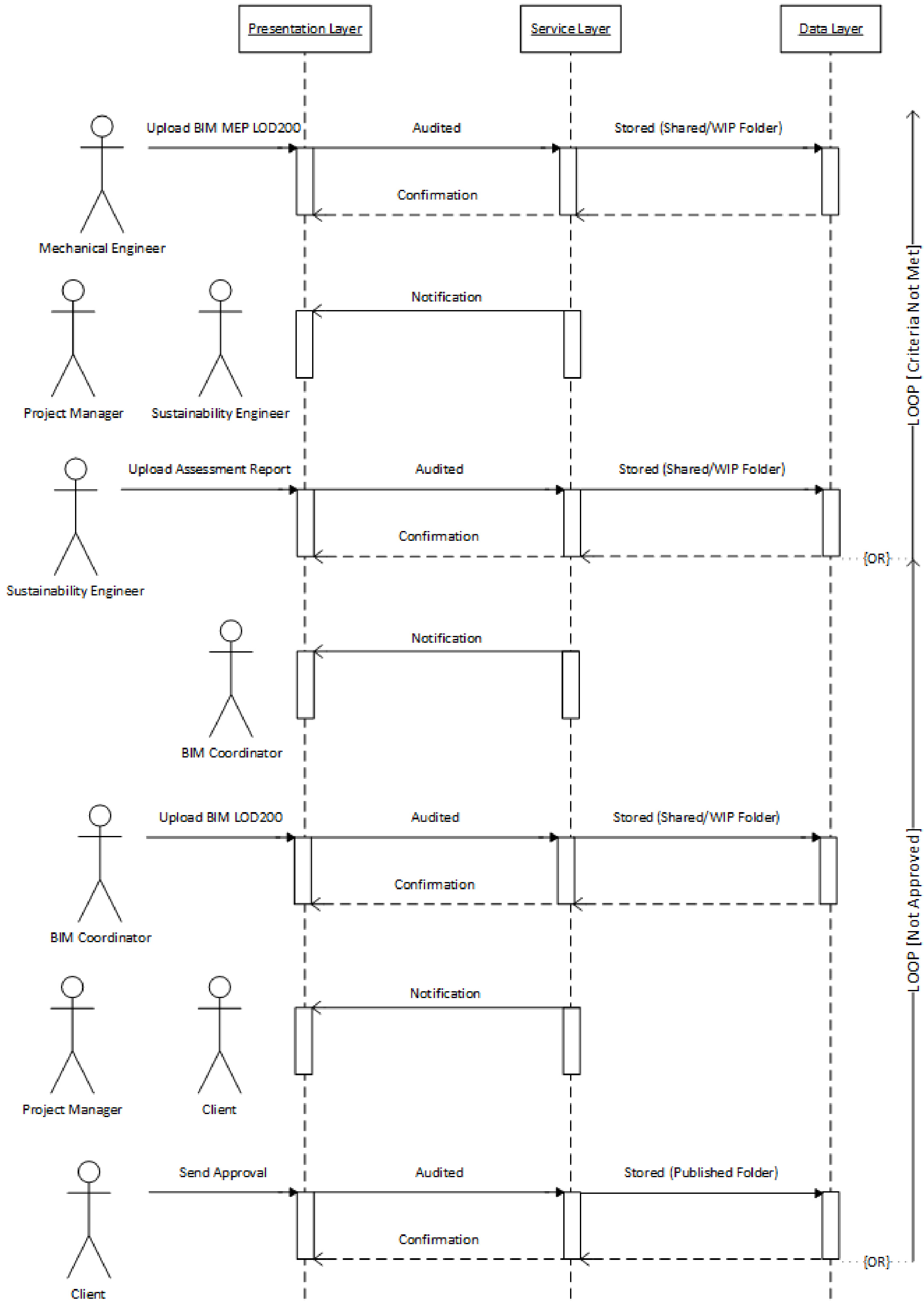


Figure 6.43 Use Case Scenario 4 – Mechanical Services [UOB 2.3] (Phase 1)

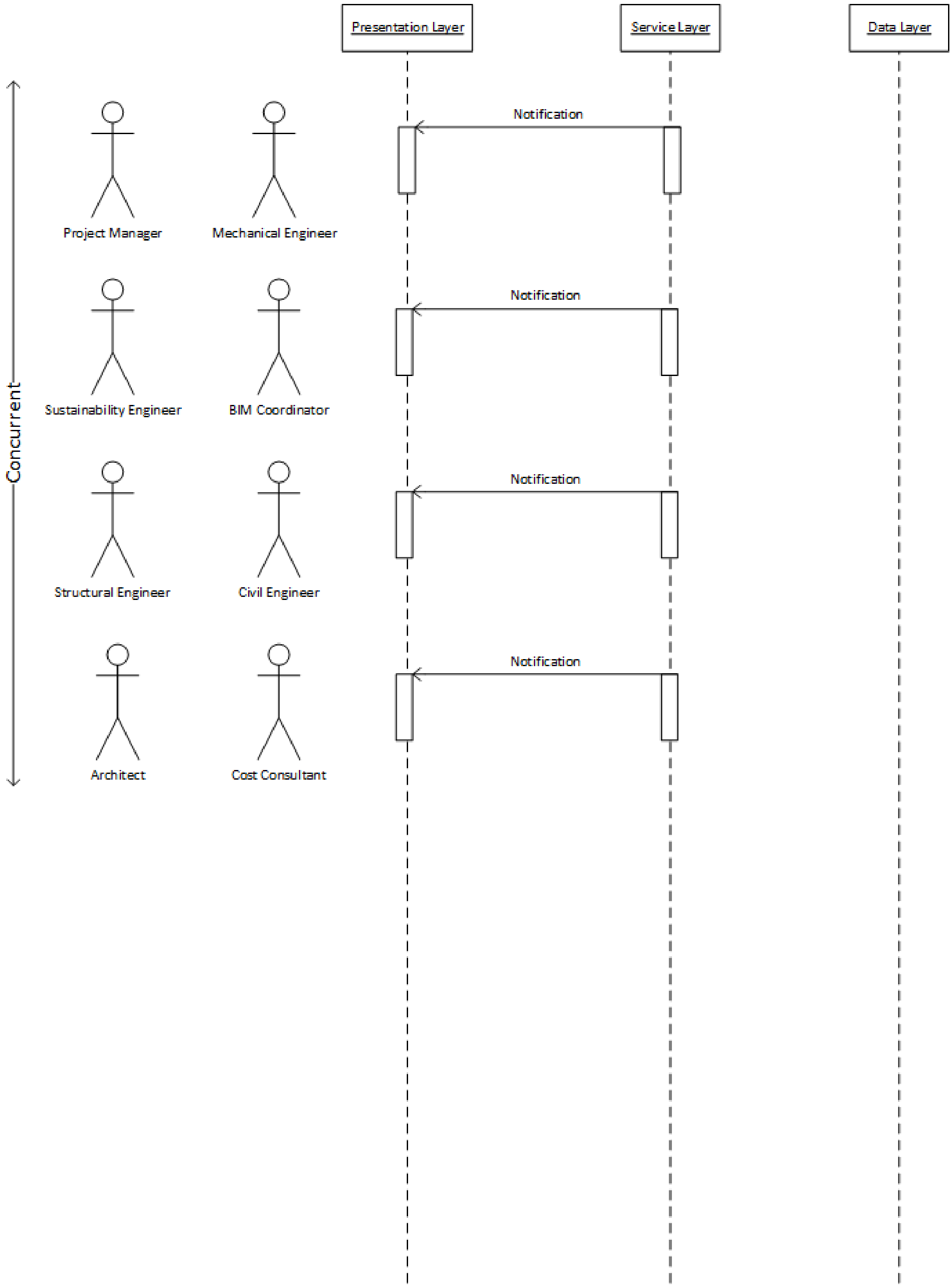


Figure 6.44 Use Case Scenario 4 – Mechanical Services [UOB 2.3] (Phase 2)

6.4.5. Use Case Scenario 5: Holistic Optimisation [UOB 2.4]

The 5th Use Case Scenario describes the sequencing of actions occurring at Phases 1, 2, and 3, during the execution of UOB 2.4 "*Develop holistic concept*". Figure 6.45 continues the process description illustrated in Figure 6.44. The notifications, sent to the stakeholders at the end of the 4th Use Case Scenario, have created four parallel threads of actions (UOB 2.4.1 to UOB 2.4.4). This means that the Architect, Structural Engineer, and MEP Engineer, work concurrently to optimise the design by following the Level 3 sub-processes' decompositions of the IDEF3 model. Once each practitioner completes their task, the Project Manager is notified by the system with an asynchronous message. After UOBs 2.4.1 to 2.4.4 are completed, and the files are stored in the Data and Knowledge Access layer, the system notifies the BIM Coordinator to initiate UOB 2.4.5. When the coordination is completed and approved (end of Phase 1), the system prompts the Sustainability Engineer and Cost Consultant to perform their tasks (UOBs 2.4.7 to 2.4.8, and 2.4.11 respectively, see Figure 6.46). These processes occur concurrently following similar communication patterns among the three layers of the system during Phase 2 (upload, audit, and store). Based on the IDEF process, the Client's Approval might create a loop in the sequence of actions (Phase 2). When the Client Approves the Concept Design Drawings, Holistic Sustainability Report, and Cost Estimation Report, the Concept Design is Signed-off. Asynchronous messages are, then, sent to the stakeholders involved in RIBA stage 2 regarding this milestone (see Figure 6.47). Furthermore, the system prompts for definition of UOB 3 (Developed Design Stage).

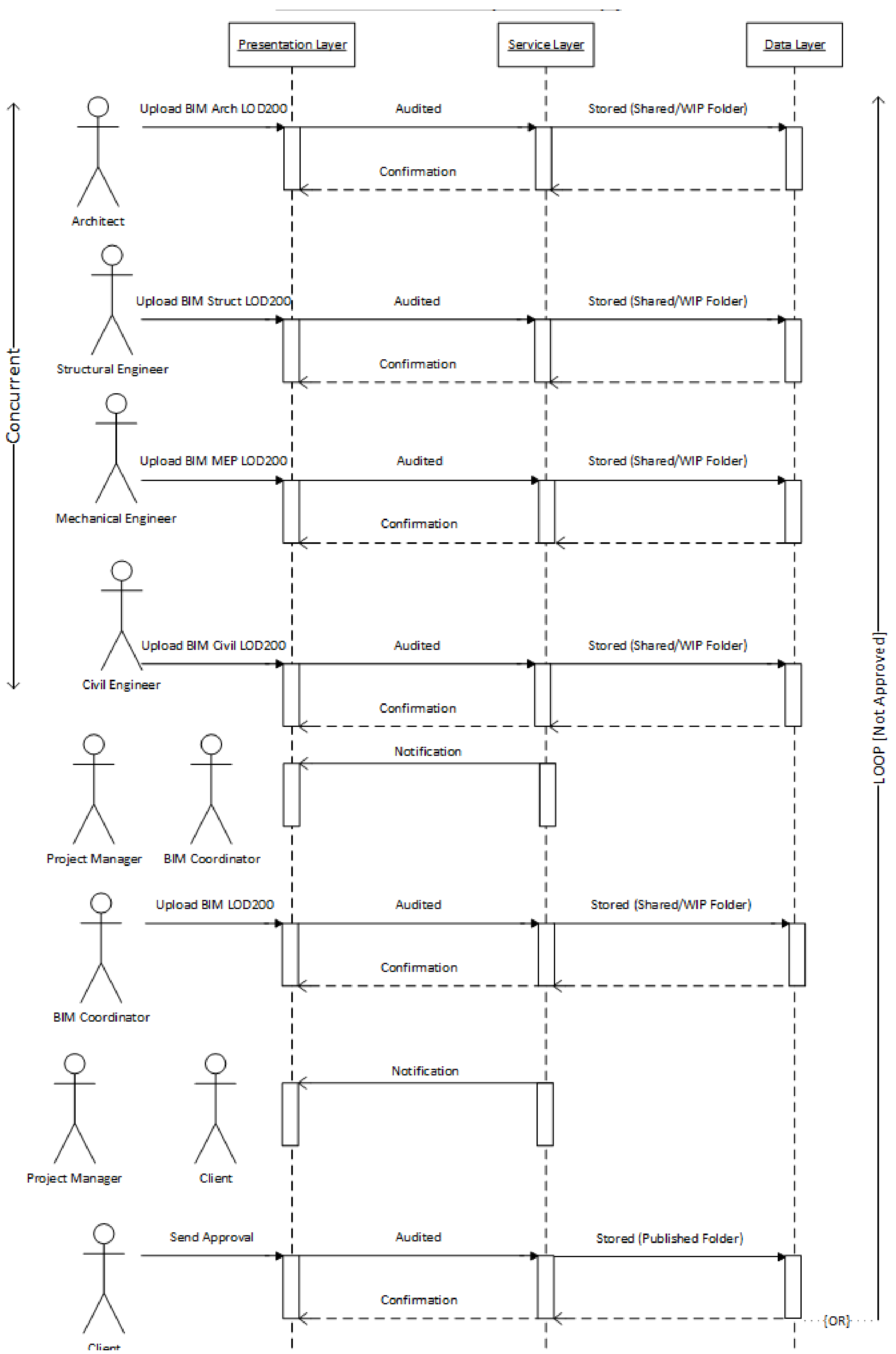


Figure 6.45 Use Case Scenario 5 – Holistic Optimisation [UOB 2.4] (Phase 1)

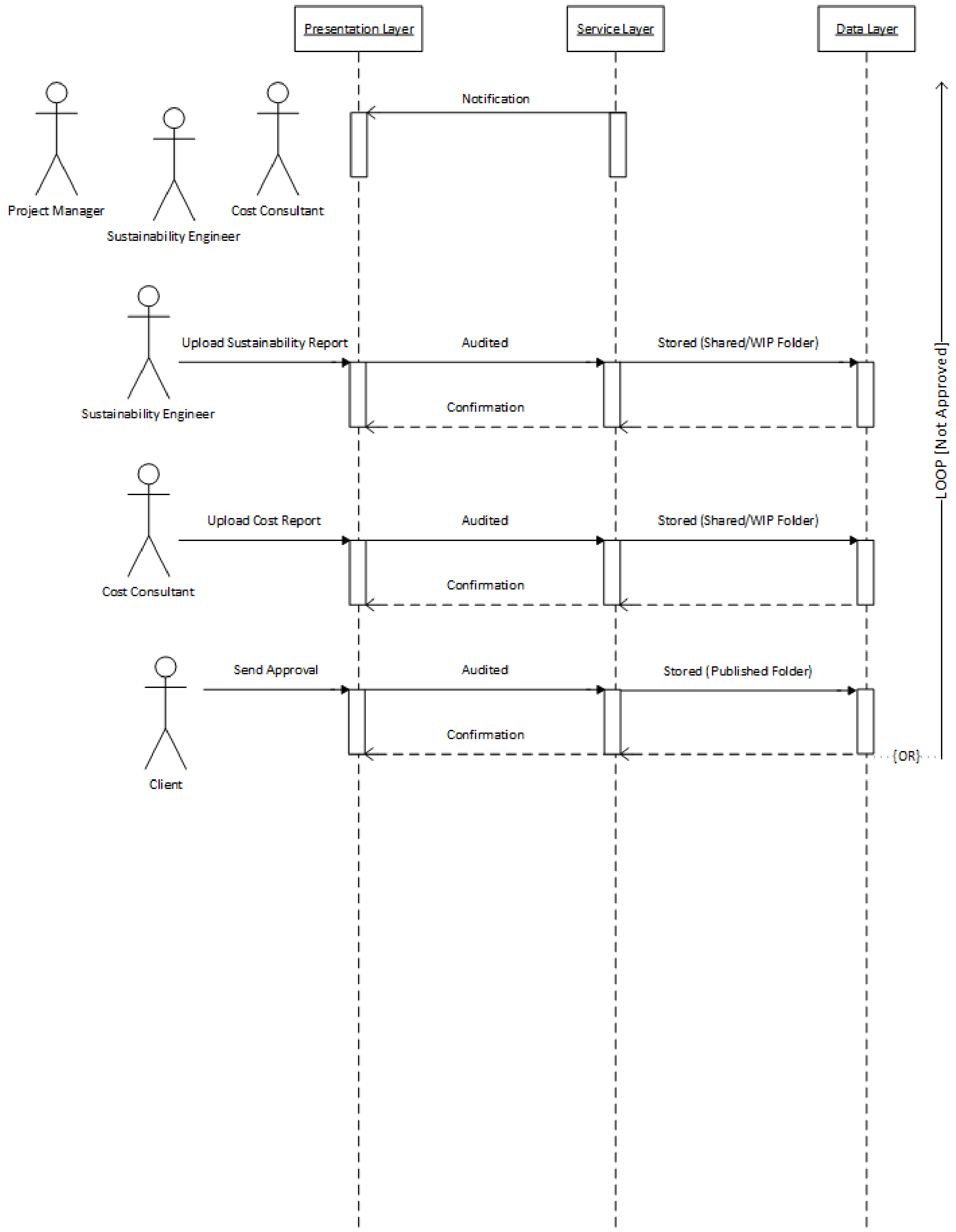


Figure 6.46 Use Case Scenario 5 – Holistic Optimisation [UOB 2.4] (Phase 2)

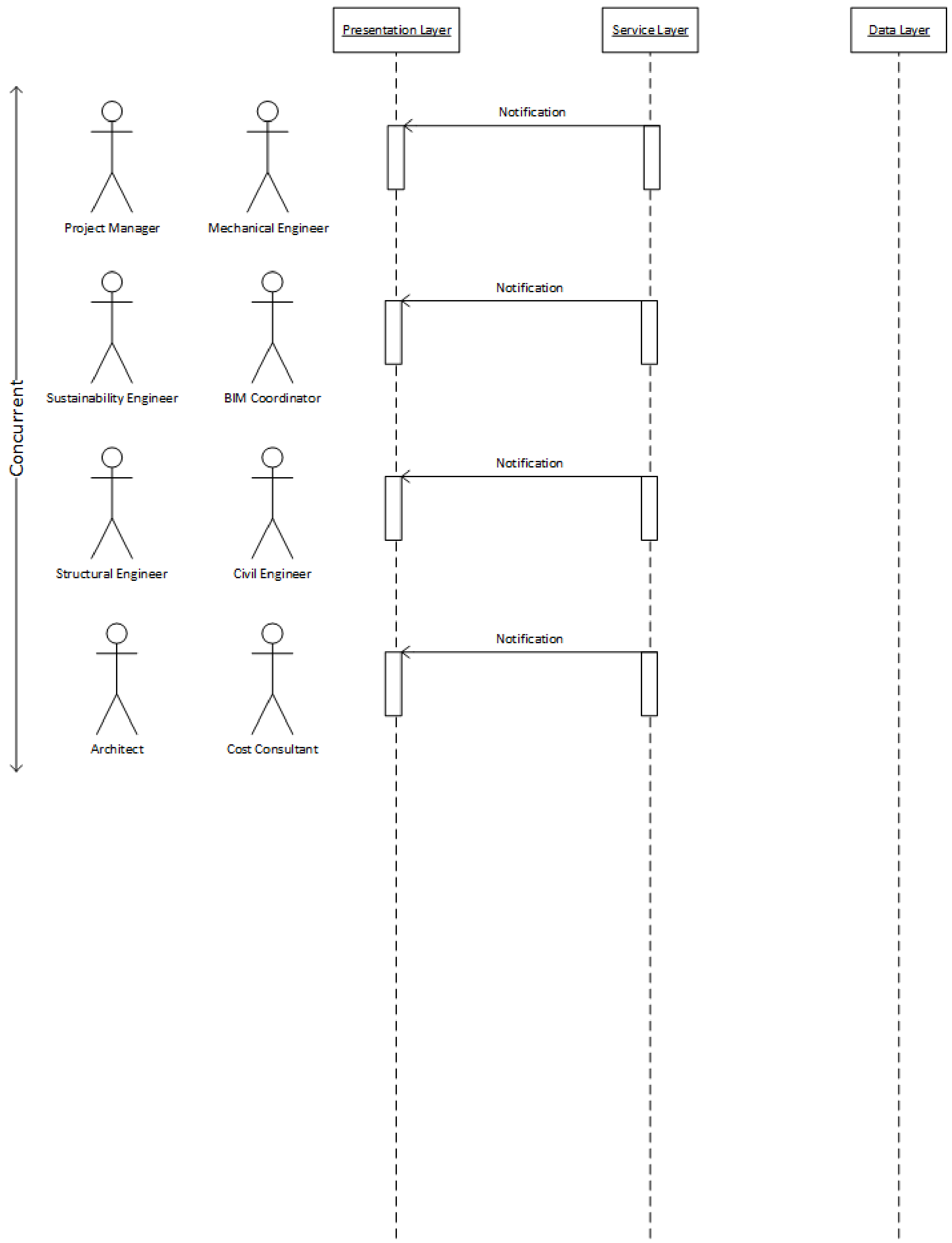


Figure 6.47 Use Case Scenario 5 – Holistic Optimisation [UOB 2.4] (Phase 3)

6.5. Summary

This Chapter has identified the patterns that currently exist during early collaborative SBD development (RIBA stages 0, 1, and 2), and coordinated them into a structured holistic process. So as to move from the spider-web communication architecture to a hub-centric one, the existing communication methods of the best practices have been mapped utilising IDEF3 CE process modelling (Mayer et al., 1995). Twenty (20) narratives have been analysed to identify the tasks, deliverables, and information requirements that occur during Concept Design (RIBA stage 2). In order to automate communication during design development, soft-gates have been identified for the critical decision points, and aligned with design criteria and benchmarks. As a result, the identified patterns have been coordinated explicitly in a systematic process for BIM-enabled SBD implementation (see Appendix D). Furthermore, the logical decisions and the commands of the IDEF process model can be used as the Service layer of a workflow management system for BIM-enabled SBD delivery. The GBB workflow management concept enables transparency of the SBD process among team members, and prompts communication by clarifying responsibilities and interdependencies of tasks and deliverables. Automated asynchronous messages (e.g. notifications) can be sent when actions need to be undertaken, or for informing the users regarding constraints, and progress. Thus, by enabling multiple viewpoints and perspectives of a holistic SBD process, a wide range of stakeholders, with varying areas of expertise, are engaged efficiently.

The next Chapter reviews the feedback received from the SBD experts during workshops (with academic peers) and interviews (with industry practitioners). Then, it presents the final IDEF process model revised according to their recommendations.

Chapter 7

Validation of research outputs and model refinement

7.1. Introduction

The objective of this Chapter is to establish the trustworthiness of the research outcomes through academic and industrial reviews. The validation criteria of credibility, dependability, confirmability, and transferability have been discussed in Section 4.7.4 (of Chapter 4). First, Section 7.2 summarises the design of the validation exercises performed during this study. Then, Sections 7.3 and 7.4 report the methods and feedback received from academic workshops and interviews with industry practitioners. Section 7.5 presents the IDEF process model for BIM-enabled SBD, amended to accommodate the recommendations made by the industrial participants. Finally, Section 7.6 summarises the main findings of the Chapter.

7.2. Validation cycles

Given the iterative nature of the research study (Meredith, 1993; Gay, 2011), which has followed an abductive methodology, the research outputs have been evaluated in eight cycles that have led to the validation and refinement of the process model for BIM-enabled collaborative SBD. Table 7.1 contains the stages of model development aligned with the research phases presented in Chapter 4, Section 4.7. The first validation point has been a peer reviewed paper in the *Sustainable Building and Construction Conference (SB13)* at Coventry University, in July 2013. The second validation point has been with industry practitioners, when the high-level IDEF process model was presented to them during exploratory interviews with 5 participants (Phase 1). Furthermore, the IDEF process model has been published in a conference paper presented in the *6th CECAR (Civil Engineering Conference in the Asian Region)* that took place in August (20-22) 2013, in Jakarta (Indonesia). The fourth validation point, for the IDEF process model, was an article published in the

International Journal of Energy Sector Management 8 (4), 562-587, in 2014. The same version of the IDEF process model has been validated during 14 interviews with industry practitioners, as discussed in Chapter 6 (validation point 5). Once the data collection was completed, the IDEF model, along with the Green BIM Box (GBB) workflow management concept, were presented during two workshops with academic peers (8 participants) (validation point 6). Moreover, the IDEF model, supported by a revised version of the validation questionnaire (see Appendix B), was demonstrated and discussed with seven (7) industry practitioners (validation point 7). The final version of the IDEF process model has been published in the *Architectural Engineering and Design Management* journal, in August 2016 (validation point 8). The papers' abstracts and publication details, including publishers' links, can be found in Appendix A.

Table 7.1 Validation cycles during iterative process model development

Point	***Phase***	***Stage of development***	***Type of validation***
1	1	Initial/preliminary framework	Academic (SB13 conference paper)
2	1	High-level IDEF0 initial	Industry (Interviews, 5 participants)
3	2	Theoretical framework / High-level IDEF0 initial	Academic (CECAR6 conference paper)
4	2	Theoretical framework / High-level IDEF0 initial / Detailed IDEF3 decompositions Initial	Academic (IJESM journal article)
5	2	Detailed IDEF3 decompositions Initial	Industry (Interviews, 14 participants)
6	3	Theoretical framework / High-level IDEF0 Final / Detailed IDEF3 decompositions Final	Academic (2 workshops, 8 academic peers)
7	3	Theoretical framework / High-level IDEF0 Final / Detailed IDEF3 decompositions Final	Industry (Interviews, 7 participants)
8	3	Theoretical framework / High-level IDEF0 Final / Detailed IDEF3 decompositions Final	Academic (AEDM journal article)

7.3. Evaluation workshops with academic peers

Two internal workshops were performed with academic peers, who specialise in SBD (8 participants). These also served as pilots for testing the method and questionnaire before the industry evaluation. This Section discusses the feedback received during the workshops (validation point 6), and how it has shaped the next validation cycle of the research (validation point 7). Table 7.2 contains the profiles of the academic participants.

7.3.1. Workshops' structure

At the beginning of the workshop, the participants were provided with the following documents (see Appendix B): (i) participant information sheet, (ii) consent forms (researcher and participant copy), (iii) presentation handout, (iv) questionnaire handout, and (v) workshop evaluation form.

First, the purpose and structure of the workshop were explained. Then, the presentation (see Appendix B) was performed into 4 sessions divided by 3 activity intervals, during which the participants completed the questionnaire handout sections, as instructed. The first session introduced the research problem and scope. The second session explained the theoretical framework that guides the research, the methods implemented, and the main outcomes. The third session presented the GBB workflow management tool and its benefits. The fourth session was about concluding remarks, and questions and answers. Aligning with the above sessions, the 3 activity sections of the questionnaire handout collected information regarding: (i) the background of the participants, (ii) their experience with BIM and SBD, and (iii) their attitudes towards GBB. Finally, the participants completed an evaluation form for the workshop.

7.3.2. Participants' experience

Table 7.3 summarises the main activities that the participants have undertaken in relation to SBD. The sample consisted of varying areas of expertise such as architectural design, BPA, and regulatory compliance certification schemes.

Figure 7.1 illustrates the BIM software tools that the participants have utilised for building design. Autodesk Revit has been found to be the most popular choice (5/8), followed by Graphisoft ArchiCAD (3/8), Rhino3D (3/8), and Trimble SketchUp (2/8). In addition, one of the participants (A-F) nominated Phoenix integration software.

Figure 7.2 shows the participants' choices regarding the compliance schemes for SBD. Part L of Building Regulations and Energy Performance Certificate (EPC) were the most selected ones (5/8). Passivhaus, or "*Passive House*", certification appears to be also popular in the UK (3/8). BREEAM (Building Research Establishment Environmental Assessment Methodology) and SBEM (Simplified Building Energy Model) were selected for an equal amount of times (2/5). LEED (Leadership in Energy and Environmental Design) and CDM (Construction Design Management) were also implemented by the experts (1/8). Finally, there was one participant (A-G) that had no experience with any certification scheme.

Table 7.2 Profiles of workshops' participants

Academic Participants	*Roles occupied*	*Educational background*	*Areas of expertise*	*Professional experience*	*BIM experience*	*BIM maturity*
A-A	Sustainability engineer	Bachelor in civil engineering, Master in environmental engineering	Environmental physics	3 years, 2 months	3 years, 2 months	Level 2
A-B	Civil engineer, Sustainability engineer, Energy modeller	Bachelor in civil engineering, Master in environmental design of buildings	Engineering, Sustainability	7 years	2 years	Level 1
A-C	Civil engineer, Sustainability engineer	Master in low carbon design and energy modelling	Environmental physics, Engineering, Sustainability	3 years, 3 months	3 months	Level 2
A-D	Lighting engineer	Master in architectural engineering	Architecture, Engineering, Sustainability	2 years, 1 month	2 years	Level 1
A-E	Civil engineer, Cost consultant	Master in low carbon design and energy modelling, Master in energy demand in the built environment	Engineering, Sustainability	6 years	3 years	Level 1
A-F	Civil engineer, Energy modeller	Master in low carbon design and energy modelling, Master in energy demand in the built environment	Engineering, Sustainability, Geotechnical engineering	N/A	N/A	Level 1
A-G	PhD student	Bachelor in geography, Master in energy policy, Master in energy demand in the built environment	Sustainability, Energy policy	N/A	N/A	Level 0
A-H	Architect/Lead designer	Master in architectural engineering	Architecture, Engineering, Sustainability	2 years	7 years	Level 1

Table 7.3 Participants' experience with sustainable building design

Academic Participants	*Experience with sustainable building design*
A-A	• Dynamic thermal modelling (IES-VE, EnergyPlus, TAS) • POE (Post Occupancy Evaluation) - building performance analysis • BIM - simulation root integration (Dynamo, IES-VE, Grasshopper, ladybird, honeybee) Integrating disparate working loads between Mech, Eng, building physics and sustainability analysis - data generated by, passed via Python/Dynamo and utilised by another.
A-B	• Energy inspections and certificates • Accreditor of LEED Green Associate • Retrofits
A-C	• 3 years, building physics for PhD purposes (energy performance/heat transfer for retrofit decision making) • 3 months, BIM to BEM. From gbXML files to idf files for energy analysis of existing buildings
A-D	• University: thermal energy calculations, compliance to green standards (Passivhaus), site specific building design for daylight access/shading • Professional: Evaluation of a school design in hot climate for the best use of natural daylight and to limit overheating
A-E	• Quantitative and qualitative daylight thermal evaluation of vernacular education buildings in Greece (advanced simulation) • Parametric studies of low carbon strategies
A-F	• MRes dissertation on demand control natural ventilation of plus energy houses
A-G	• Experience modelling with SAP 2009 and EnergyPlus / DesignBuilder (student project)
A-H	• Sustainable building design in the content of architectural competition • PhD Studies: research related to building performance simulation, lab assistance to students on tools such as Revit and Navisworks

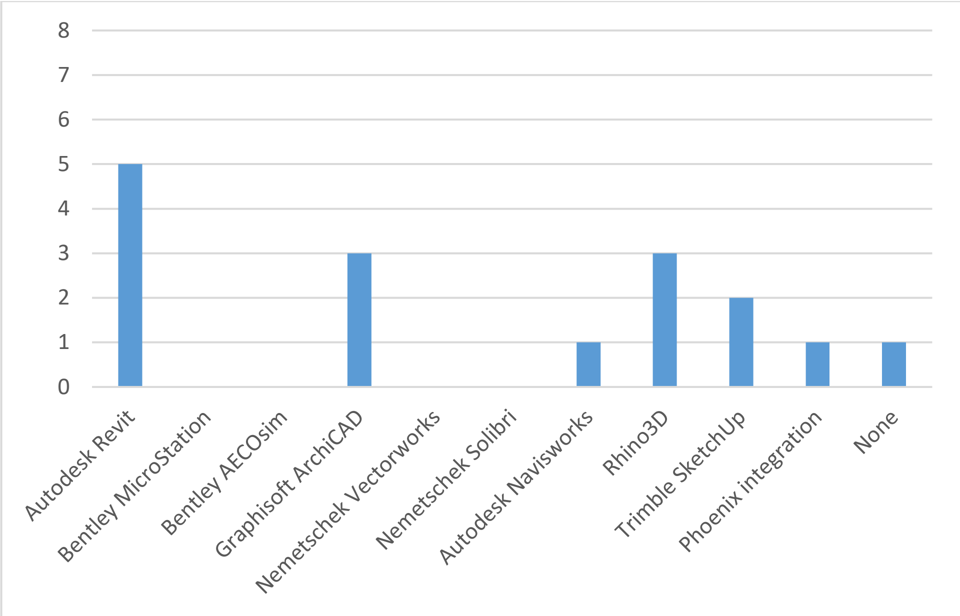


Figure 7.1 Building Information Modelling (BIM) software tools utilised for building design

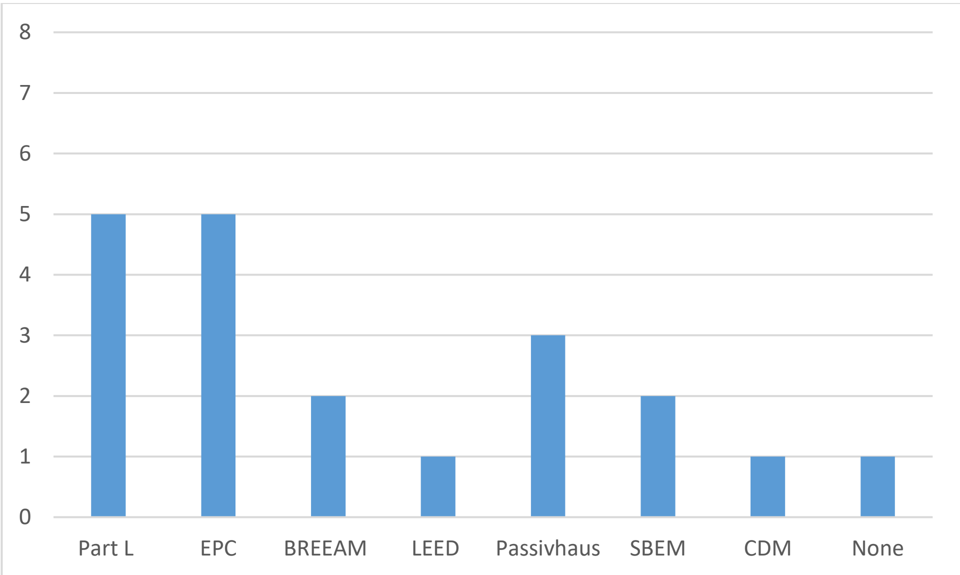


Figure 7.2 Sustainability compliance schemes utilised to certify sustainability in building design

Section 2 of the questionnaire contained information regarding the collaboration means and methods utilised for exchanging information between project team members. This part of the questionnaire was found to be more time consuming to complete than expected. Hence, it has been simplified for the next stage of validation interviews (with industry practitioners).

Interestingly, out of the 17 options of Online Collaboration Platforms (OCPs) provided in the questionnaire (question 10); 7/8 stated that they utilised Dropbox for information exchanges; 2/8 respondents selected the Private Extranet or "*Company's workspace*" option; 2/8 participants nominated Google Drive; and 1/8 has been using MS SharePoint, MS OneDrive for Business, and Flow.io for implementing SBD.

Figure 7.3 shows the familiarity that the respondents had with the existing BIM standards. Five (5/8) participants have not used any standard, while two (2/8) have implemented the RIBA Plan of Work 2013, BS 1192:2007 (Collaborative production of architectural, engineering and Construction information), and PAS 11922: 2013 (Specification for information management for the capital/delivery phase of construction projects using building information modelling). Furthermore, one (1/8) have used the GSL (Government Soft Landings), Digital Plan of Work (DPoW, NBS BIM Toolkit), and Classification - Uniclass2015. Moreover, none of the participants were familiar with the CIC Building Information Model (BIM) Protocol. Therefore, it can be inferred that although the academic peers, who participated in the workshops, are all experts in SBD by being knowledgeable about implementing methods that assist in achieving environmental design goals, the majority of them cannot be qualified as BIM experts. Nevertheless, their input is considered valuable for validating the SBD framework.

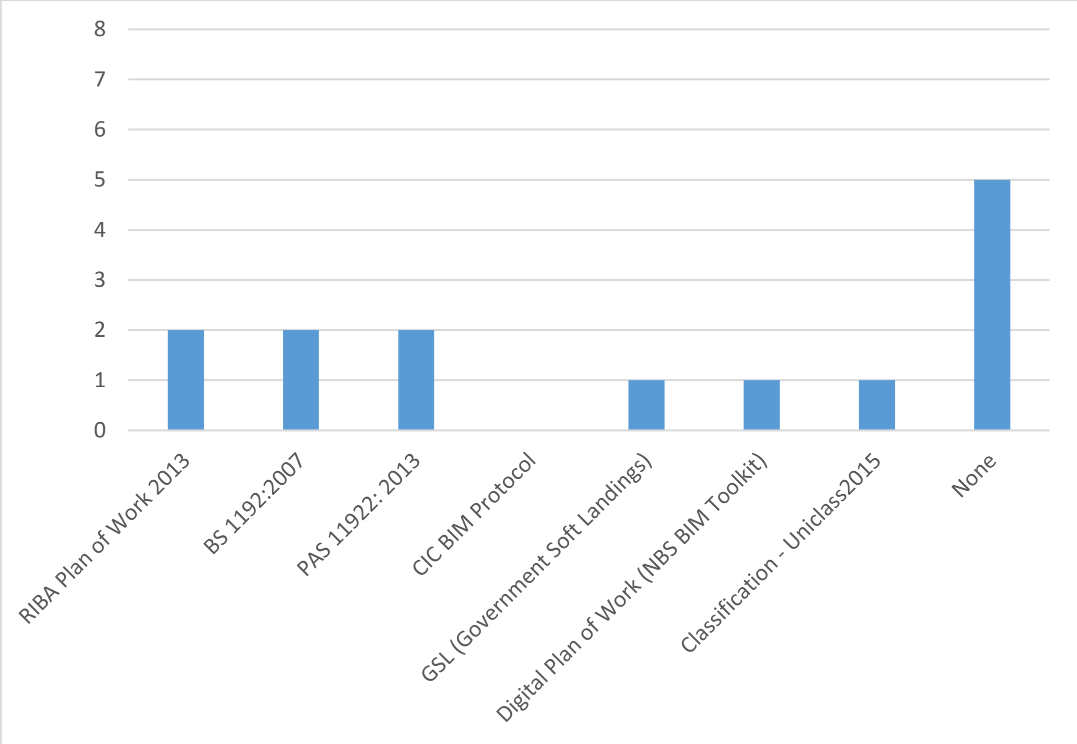


Figure 7.3 BIM standards implementation

Table 7.4 contains the participants' responses regarding the BPA software that they have used to assess environmental design considerations. It is found that a variety of specialised tools are needed to improve the accuracy of performance simulations. Nevertheless, software tools such as IES-VE, DesignBuilder, and EnergyPlus offer extensiveness that can cover most aspects of SBD.

Figure 7.4 illustrates the participants' attitudes regarding a standardised process for BIM-enabled SBD. The research hypothesis has been positively received overall. In instances where the participant has disagreed, the researcher has performed follow up questions to clarify the participant's reasoning behind the answer. It has been realised that negative responses have been given due to misunderstanding the intent of the questionnaire's statements. As soon as the intent of the statements was explained, the participants agreed with them confidently. Based on this feedback, the questionnaire for the industry validation has been revised in order to provide clearer statements.

Table 7.4 Building performance analysis tools used by the participants

Design aspect	*Workshops' participants*							
	A-A	***A-B***	***A-C***	***A-D***	***A-E***	***A-F***	***A-G***	***A-H***
Climate and weather	IES-VE, TAS, TRNSYS, Daysim + Radiance, Ecotect	EnergyPlus	IES-VE, Revit	Data analysis in Python	IES-VE	DesignBuilder, IES-VE	EnergyPlus, DesignBuilder	EnergyPlus, DesignBuilder
Massing	SketchUp, IES-VE	EnergyPlus, Diva for Rhino, Open Studio	Revit, Energy Plus, SketchUp	SketchUp, Rhino	iSBEM	Revit, EnergyPlus	EnergyPlus, DesignBuilder	EnergyPlus, DesignBuilder
Fabric	IES-VE, TAS	EnergyPlus	Revit, IES-VE, Radiance, EnergyPlus	Radiance + Daysim, IES-VE	IES-VE	IES-VE, DesignBuilder, Radiance, EnergyPlus	EnergyPlus, DesignBuilder	EnergyPlus, DesignBuilder
Services	Revit, Hevacomp, IES-VE, TAS, Bespoke	EnergyPlus	Revit, Open Studio, EnergyPlus	N/A	IES-VE	EnergyPlus	EnergyPlus, DesignBuilder	EnergyPlus, DesignBuilder
Renewables	IES-VE	EnergyPlus	IES-VE, Green Building Studio	N/A	IES-VE	N/A	EnergyPlus, DesignBuilder	N/A
Life Cycle Assessment (LCA)	N/A	N/A	Open Studio, EnergyPlus	N/A	N/A	N/A	N/A	N/A
Cost (CapEx, OpEx)	N/A	N/A	Open Studio, EnergyPlus, Green Building Studio	N/A	IES-VE	N/A	N/A	N/A

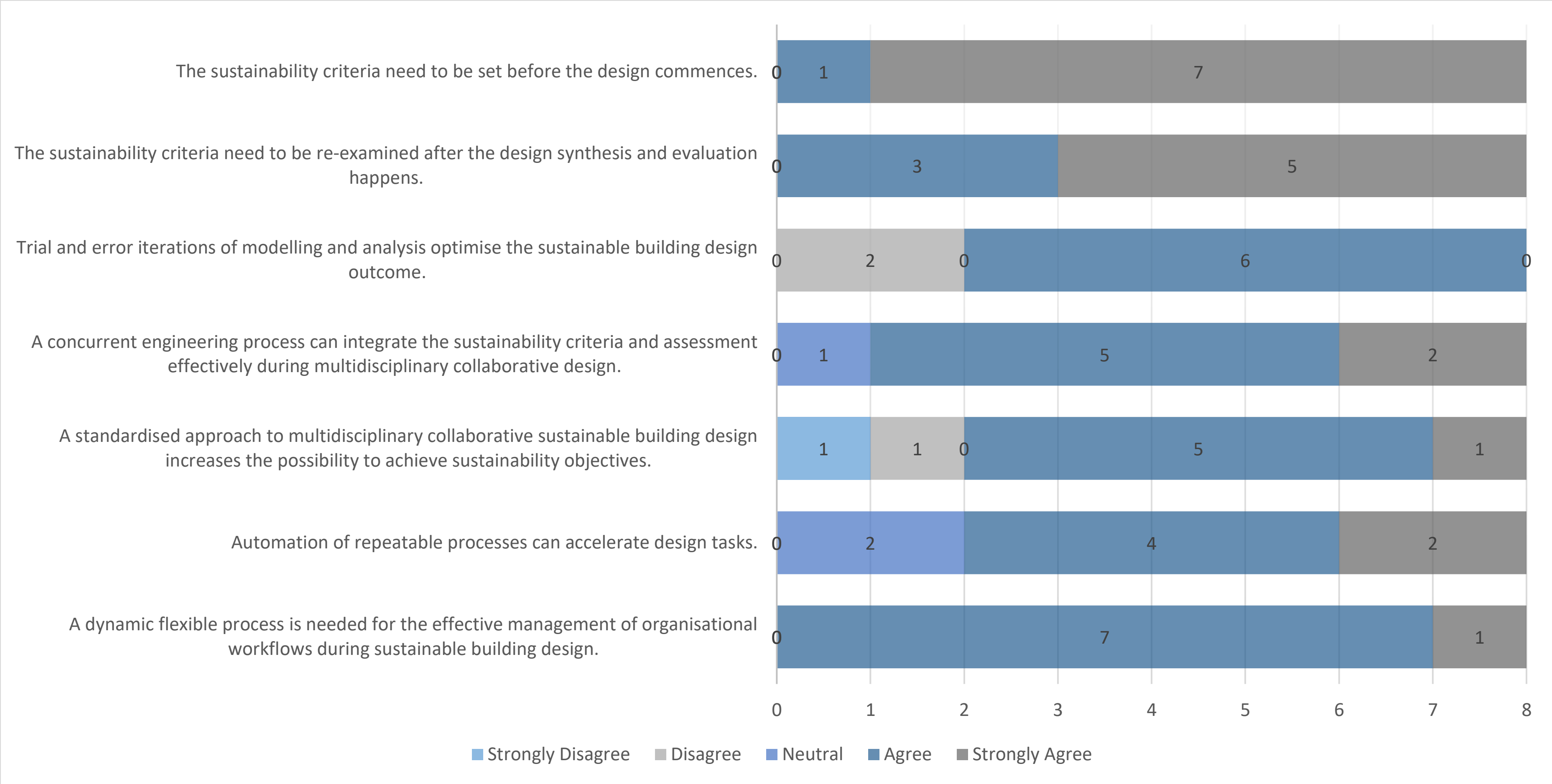


Figure 7.4 Academic participants' attitudes towards a structured BIM-enabled sustainable design process

7.3.3. Green BIM Box (GBB) evaluation

In section 3 of the questionnaire, the participants reported that GBB seemed effective in addressing *"the most important aspects of sustainability"* (Participant A-B). Furthermore, GBB is believed to be very useful in defining milestones amongst team members in order to provide with *"clarity essential for targets to be met by all stakeholders"* (Participant A-A). Thus, it is apparent that a transparent process can facilitate communication, approval, and tracking of the SBD progress. In addition, the participants believed that GBB is: (i) not complicated and is self-explanatory (Participant A-E); (ii) has the potential to assist compliance with regulations and standards (Participant A-C); and (iii) successfully integrates sustainability in the early stages of the design process (Participant A-H). Also, the Participants argued that the categories and terminology used is expressed satisfactorily.

The participants' attitudes towards GBB can be summarised in the following excerpts from the questionnaire handouts:

> *"Assists in implementing BIM-enabled sustainability in a rigorous way." (Participant A-B)*
>
> *"All considerations in one tool. Coordinate effective BIM use from start to finish." (Participant A-E)*
>
> *"Sustainability considerations are integrated from the beginning. Design process is more transparent." (Participant A-F)*

Some of GBB's limitations were stressed (by the participants) as expressed below:

> *"Specification-benchmarking is useful, but given the range of building regulations, this may be difficult." (Participant A-A)*

Some participants were hesitant due to the fact that the demonstration of GBB was limited to a video presentation during the workshop:

> *"Hard to make a decision without testing myself. All seem useful on first run through via video." (Participant A-G).*
>
> *"Need to use it first." (Participant A-F)*

"I'm not sure, I'd need to try it first." (Participant A-D)

The participants have suggested several ways that GBB could be improved such as:

- *"Less info in user interface." (Participant A-C)*
- *"Documentation and online tutorials." (Participant A-F)*
- *"Include a help menu tab for the users." (Participant A-H)*
- *"Interactive demo? Demonstrating of outputs." (Participant A-A)*
- *"Needs more colour to look modern and engaging." (Participant A-E)*

As a result, the participants unanimously agreed that they would use and/or recommend the use of GBB in the future:

- *"It is well implemented with information accurate/usable." (Participant A-A)*
- *"Yes, but the tool is missing at the moment." (Participant A-B)*
- *"Yes, it facilitates BIM to building energy modelling." (Participant A-C)*
- *I'd recommended it, it looks useful to increase awareness of the sustainability issues." (Participant A-D)*
- *"I would give it a try and observe the reaction." (Participant A-E)*
- *"I would use it because it allows for sustainability consultants to have a more active role in building design." (Participant A-F)*
- *"Yes, it can help designers to comply with building regulations from early on in the design process." (Participant A-H)*

The concluding comments about GBB have been summarised in Table 7.5. Furthermore the participants' attitudes are illustrated in Figure 7.5.

Table 7.5 summary of comments about Green BIM Box

Academic Participants	*Comments*
A-A	"Tool such as this would be useful. Is the following that should be considered: • Every project/stakeholder/methodology is different and cross platform implementation would require intensive development. Perhaps limiting it to a single (most common platform) would be easier. • Benchmarking is very complex. A database using existing building types may be useful to integrate (Carbon Trust etc.) • Open data is a must. Most organisations have their own systems and the ability to integrate would be very useful. • Visual progress notifications may help "sell" the tool. Personal experience has shown a slashy progress bar to have more effect than a bunch of text. But quantifying project development would need considerations (amount vs extent vs maturity)."
A-B	"It seems that it can integrate BIM and sustainability."
A-C	"Very useful tool for linking BIM to energy modelling. Needs some simplification to enable users to understand the process better."
A-D	"It looks like a useful tool and a required piece of any design process that cares about sustainability. I am not very informed on the subject, but if nothing like this existed previously, then it adds a fundamental contribution to the BIM strategy."
A-E	N/A
A-F	"GBB seems like a useful and effective tool that can integrate sustainability considerations on early stage of the design process."
A-G	"I think it would be a useful tool in the industry. Filling a gap in the market."
A-H	"Green BIM Box could facilitate collaboration and information flow during the design process while ensuring the compliance with the building regulations."

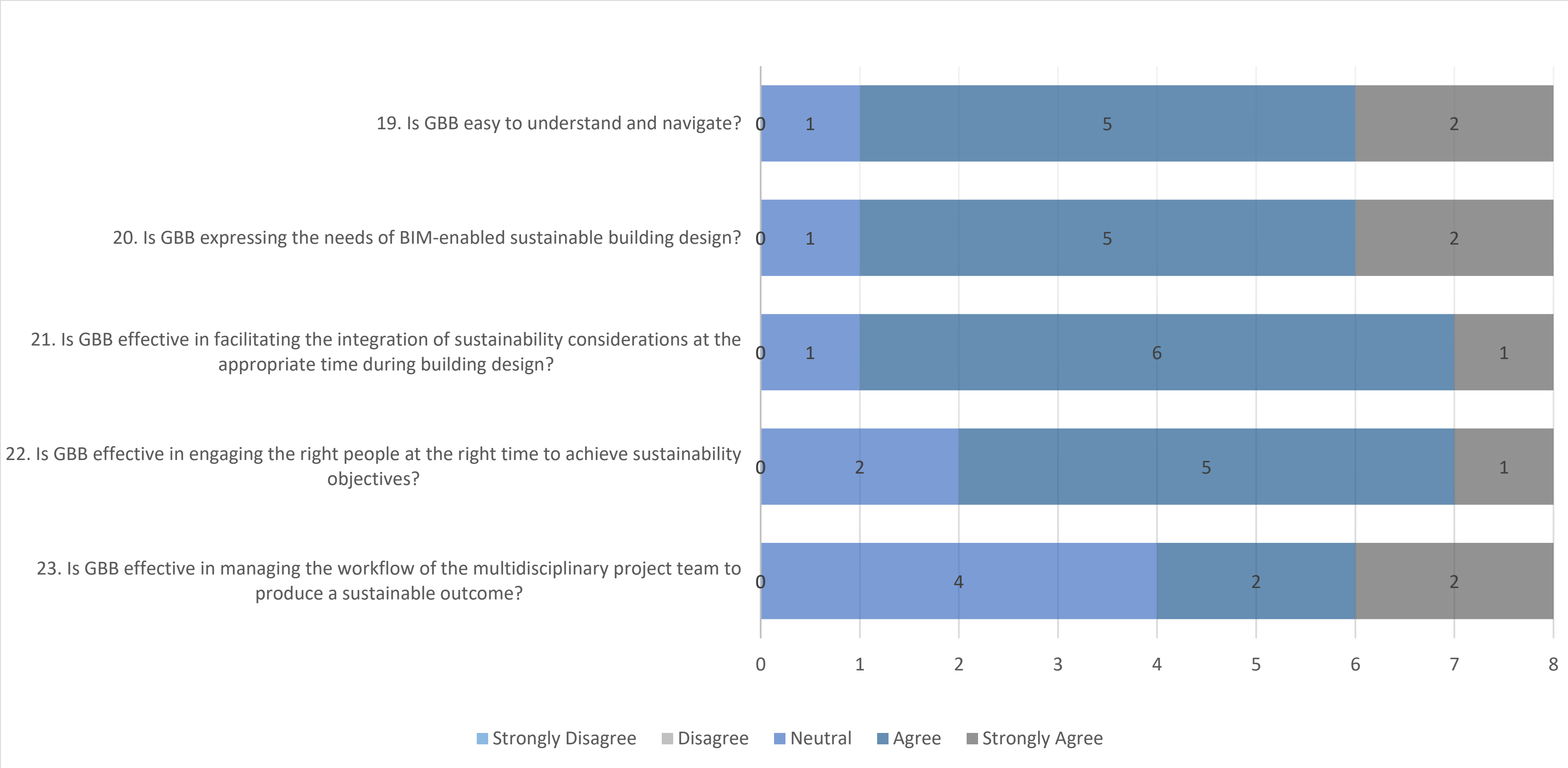


Figure 7.5 Green BIM Box evaluation

7.3.4. Workshops’ evaluation

The final act of both workshops was the evaluation questionnaire. Figure 7.6 illustrates the workshops’ evaluation criteria in detail. The feedback received was positive overall, although it varied depending on the participant’s experience with BIM. For example, Participant A-E has found the diagrams complicated to follow within the scope of the presentation:

> *"Because there are participants who understand the contents but don't constantly engage with this particular subject and complex systems graphs, give them more time to become familiar and engage with the subject." (Participant A-E)*

On one hand, Participant A-E found the presentation *“a bit too fast”,* while Participant A-A suggested that the presentation should be faster, although they both participated in the same session. The rest of the participants stated that the workshop was *“very well structured"* (Participant A-F) and *“provided a good overall background"* (Participant A-B). Additionally, the participants found the presentation to be very informative and useful for them, as demonstrated in the following statements:

> *"Good information on BIM on the presentation. Excellent introduction to Green BIM Box. The video made things easier to understand and was an effective tool for conveying the message". (Participant A-G)*

> *"Got more familiar with the integration of sustainability milestones in the design process." (Participant A-H)*

Several participants (A-C, A-D, and A-H) also noted that they would be interested in interacting with the tool themselves, as demonstrated below:

> *"Possibly having the possibility of "meeting" the tool by exploring its interface and different tabs (this may however be time consuming for the purposes of the workshop)." (Participant A-H)*

Furthermore, the participants suggested some minor alterations to the questionnaire handouts:

> *"At question 17 add heating, cooling, hot water in Energy Consumption category." (Participant A-B)*

> *"Regarding questions 15: would the client be able to answer some of those questions stated? I am not sure that the client would be able to provide such info." (Participant A-C)*

Both workshops lasted for one hour and a half each. Completing the questionnaire was found to be more time consuming than initially expected. For this reason, several questions have been simplified for the next set of evaluation interviews with the industry practitioners. The methods used, and feedback obtained during industrial evaluation, are reported in the following Section in detail.

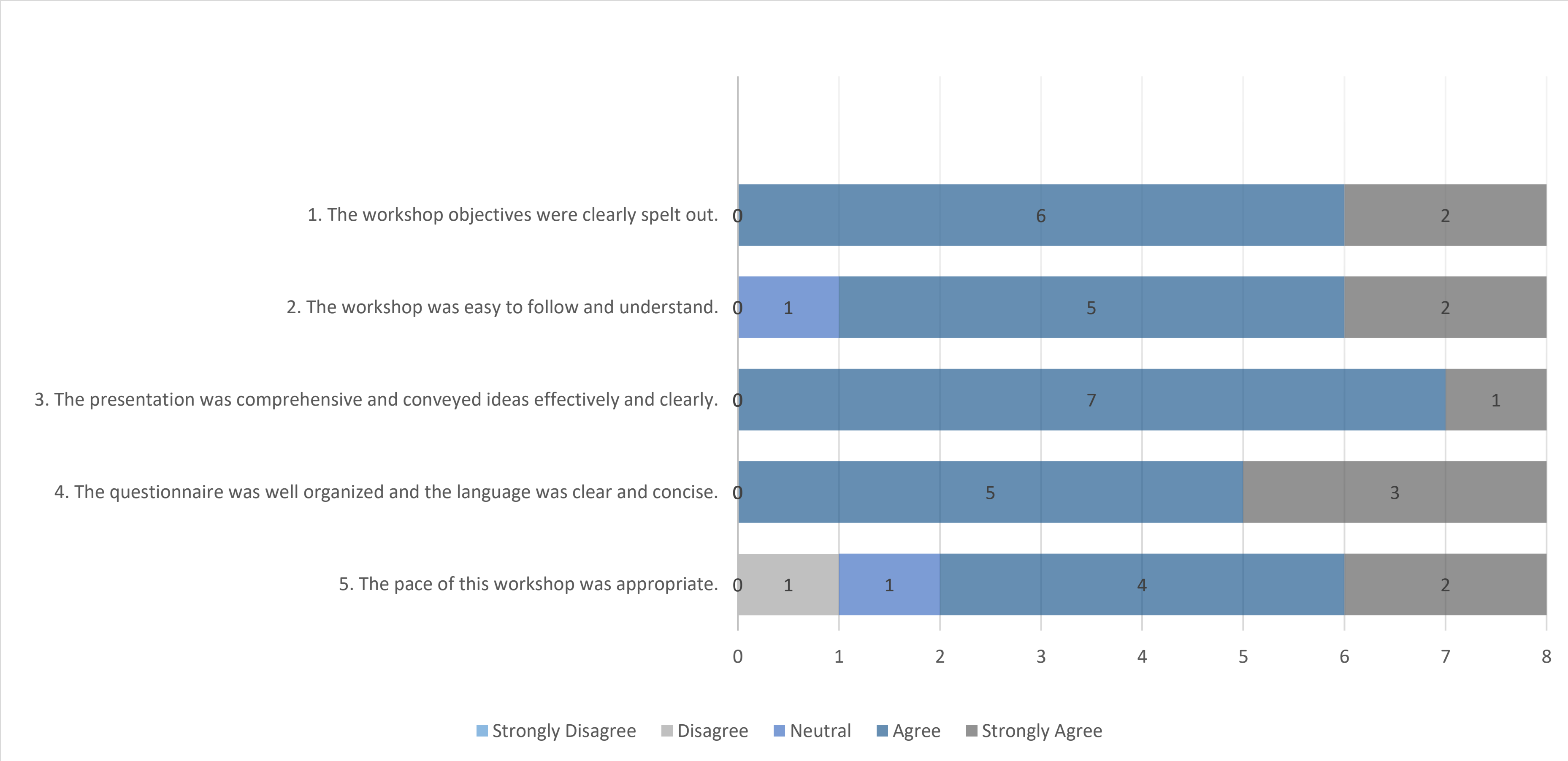


Figure 7.6 Workshops' evaluation

7.4. Model's evaluation with industry practitioners

This Section contains the feedback received during the seventh validation cycle of the research (validation point 7). The evaluation method has been informed by the feedback received during the two academic workshops. The most critical alteration suggested during the workshops was that it would be useful for the participants to examine the developed process model themselves. Therefore, in order for the practitioners to be able to familiarise themselves with the IDEF process model, its description along with the questionnaire handouts were provided to them in advance of the interviews (see Appendix B). This method has served to evaluate the IDEF process model's credibility, dependability, confirmability, and transferability (Lincoln and Guba, 1985) directly. The participants were selected based on criteria of relevant practical experience, and the sample included both experts that participated during the main data collection stage (Phase 2) as well as participants that had never been involved with the research project before. This strategy took place to ensure both the internal and external validity of the research outcomes. The objectives of the interviews were:

- To determine the industry practitioners' views towards a structured approach for SBD implementation;
- To examine the completeness of the research output in integrating sustainability considerations adequately into the building design process;
- To gather the practitioners' attitudes towards the feasibility of a workflow management system for BIM-enabled SBD.

7.4.1. Interviews' structure

Table 7.6 contains the guide that was followed during the evaluation interviews. The first section of the questionnaire contained introductory questions regarding the participant's experience with BIM and SBD. The second section of the questionnaire was transitional, designed to collect attitudes. The third section included questions that requested to evaluate the research outcomes. For previous participants, the questionnaires were adapted accordingly to avoid repetition.

Table 7.6 Interview evaluation guide

Section 1: Introductory information

- Name and organisation
- Role/s in organisation (e.g. Architect, Sustainability Engineer, Energy modeller)
- Educational background (e.g. Bachelor, Master, Doctorate)
- Professional experience (e.g. years, types of projects)
- Skills and competencies (e.g. main duties, job description)
- Areas of expertise (e.g. sustainability, environmental physics)
- Experience with BIM (e.g. level of maturity, software tools used)

Section 2: Transitional statements

Attitudes towards (five point scale, Strongly agree – Strongly disagree):

- The sustainability criteria need to be set before the design commences.
- The sustainability criteria need to be re-examined after the design synthesis and evaluation happens.
- Trial and error iterations of modelling and analysis optimise the sustainable building design outcome.
- A concurrent engineering process can integrate the sustainability criteria and assessment effectively during multidisciplinary collaborative design.
- A standardised approach to multidisciplinary collaborative sustainable building design increases the possibility to achieve sustainability objectives.
- Automation of repeatable processes can accelerate design tasks.
- A dynamic flexible process is needed for the effective management of organisational workflows during sustainable building design.

Section 3: Research outcomes' evaluation

- Do you believe that the model captures the BIM-enabled sustainable building design process adequately? Why?
- Would you add or remove any of its activities, deliverables, or milestones? Which ones and why?
- Are the categories and their contents expressed in a satisfactory way? What changes would improve understanding?
- In what ways can the model be improved?
- Do you find such a model useful? Why?
- What do you believe are the benefits of a structured process for sustainable building design?
- Would you use and/or recommend the use of Green BIM Box in the future? Why?
- What do you believe are the capabilities and features needed in order to facilitate BIM-enabled sustainable building design within a Common Data Environment (CDE)?
- Please summarise your views about Green BIM Box workflow management system.

7.4.2. Participants' experience

Table 7.7 contains the profiles of the industrial participants that were interviewed. Interviews I-A, I-B, I-C, and I-D were digitally recorded, while interviews I-E, I-F, and I-G have been transcribed in the form of handwritten notes on the questionnaire handouts. Each interview lasted from 45 minutes to 1.5 hours. Table 7.8 summarises the participants' experience with BIM-enabled SBD. The Interviewees' skills have covered a wide range of BIM specialisations such as integration of BIM with BPA tools (I-A and I-B), BIMs' coordination (I-C), BPA modelling (I-D, I-E, and I-G), and architectural design utilising BIM (I-C and I-F).

Table 7.7 Profiles of interviews' participants

Industrial Participants	*Roles occupied*	*Educational background*	*Areas of expertise*	*Professional experience*	*BIM experience*	*BIM maturity*
I-A	MEP Engineer, Sustainability Engineer, Energy Modeller, BIM Specialist	Build Environment Computational Engineer, Environmental Engineer (Master)	Environmental Physics, Engineering, Sustainability, Computer programming	10 years	10 years	Level 2 – Level 3
I-B	Sustainability Consultant, Energy model, BIM Specialist	Doctorate in Physics	Environmental physics	5 years	3 years	Level 1 – Level 2
I-C	BIM Manager/Coordinator	Bachelor Design Arts	BIM architectural modelling	13 years	10 years	Level 2
I-D	Sustainability Engineer, Energy Modeller	Master in Building Physics	Engineering, Environmental Physics, Sustainability	3 years	3 years	Level 1 – Level 2
I-E	Civil Engineer, Sustainability Engineer, Energy Modeller	Bachelor in Civil Engineering, Master in Environmental Design, Doctorate in Performance Gap	Engineering, Environmental Physics, Sustainability	9 years	5 years	Level 1 – Level 2
I-F	Architect/Lead Designer, Sustainability Engineer	Bachelor in Architecture, Master in Environmental Design of Buildings	Architecture, Sustainability	4 years	9 years	Level 1
I-G	Sustainability Engineer, Energy Modeller	Bachelor in Architecture, Master in Environmental Design, Doctorate Building Energy	Architecture, Sustainability, Environmental Physics	7 years	13 years	Level 1 – Level 2

Table 7.8 Participants' experience with BIM-enabled sustainable building design

Industrial Participants	*Types of buildings*	*Compliance*	*BIM tools*	*BPA tools*	*Online Collaboration Platforms (OCPs)*
I-A	Commercial, schools, sport, banks	Part L, LEED, BREEAM, ASHRAE, CIBSE	Revit, Revit plug-ins, Rhino	Tasmanian Devil, TAS, DYNAMO, Honeybee Ladybug, Radiance, Daysim, Mustafa, Building Studio	Company network
I-B	Non-domestic, stadiums, hotels, schools	EPC, LEED, BREEAM, Part L (UK), AHRAE (USA)	Revit MEP	IES-VE, TAS, Diva	Database
I-C	Non-domestic, offices, commercial	Part L, EPC, BREEAM	Revit, ArchiCAD, Navisworks, Solibri	Sefaira, EcoDesigner, IES-VE	4Projects
I-D	Non-domestic, domestic	EPC, Part L, BREEAM	Rhino, Revit, AutoCAD, Solibri, Navisworks	Sefaira, Diva, Grasshopper, IES-VE	CDE
I-E	Non-domestic (construction), domestic (energy inspection)	LEED	Revit, AutoCAD, SketchUp, Rhino	Ecotect, EnergyPlus, Radiance, Daysim	Dropbox, Google Drive, Excel macro commands for workflow management
I-F	Residential, domestic	Code for Sustainable Homes	Revit, AutoCAD, SketchUp	Ecotect, Radiance	Dropbox
I-G	domestic, non-domestic	EPC, Part L, BREEAM	ArchiCAD, Revit	Ecotect, EnergyPlus, IES-VE	Company network

7.4.3. Participants’ attitudes towards BIM-enabled SBD

Figure 7.7 demonstrates the industrial participants’ attitudes towards a structured BIM-enabled process for SBD. All the Interviewees have either agreed or strongly agreed with the statements presented to them. Some sentences, though, required further clarifications from the researcher to better communicate their intent. Once the intent was clarified, the participants were able to respond with confidence. Moreover, the concept of GBB was very positively received; the more involved a participant was with BIM, the more enthusiastic their response.

7.4.4. Importance and relevance of the research output

All participants recognised the need for a structured and standardised BIM-enabled process for SBD. It has been established that the main principles that this process should follow are: (i) clear definition of sustainability objectives before design implementation and delivery, (ii) frequent feasibility checks for sustainability goals/benchmarks, (iii) iterative process of building design and sustainability assessment, (iv) concurrent parallel tasks, and (v) clear rules with an amount of customisation for bespoke projects. The participants believed that automation of workflow management, for SBD, can assist in achieving sustainability objectives in the most economical way possible in terms of time, cost, and effort.

All participants considered the research output to be very well-structured, clear, relevant, comprehensive, and easy to understand and navigate. Furthermore, they acknowledged its significant value as a guideline for considering the most critical aspects of sustainability at concept design stage, and also, for communicating them among the design team for better alignment. The details of their evaluation along with recommendations for improvement are discussed in the following sub-Sections. Moreover, the final refined model is presented in Section 7.5 of this Chapter.

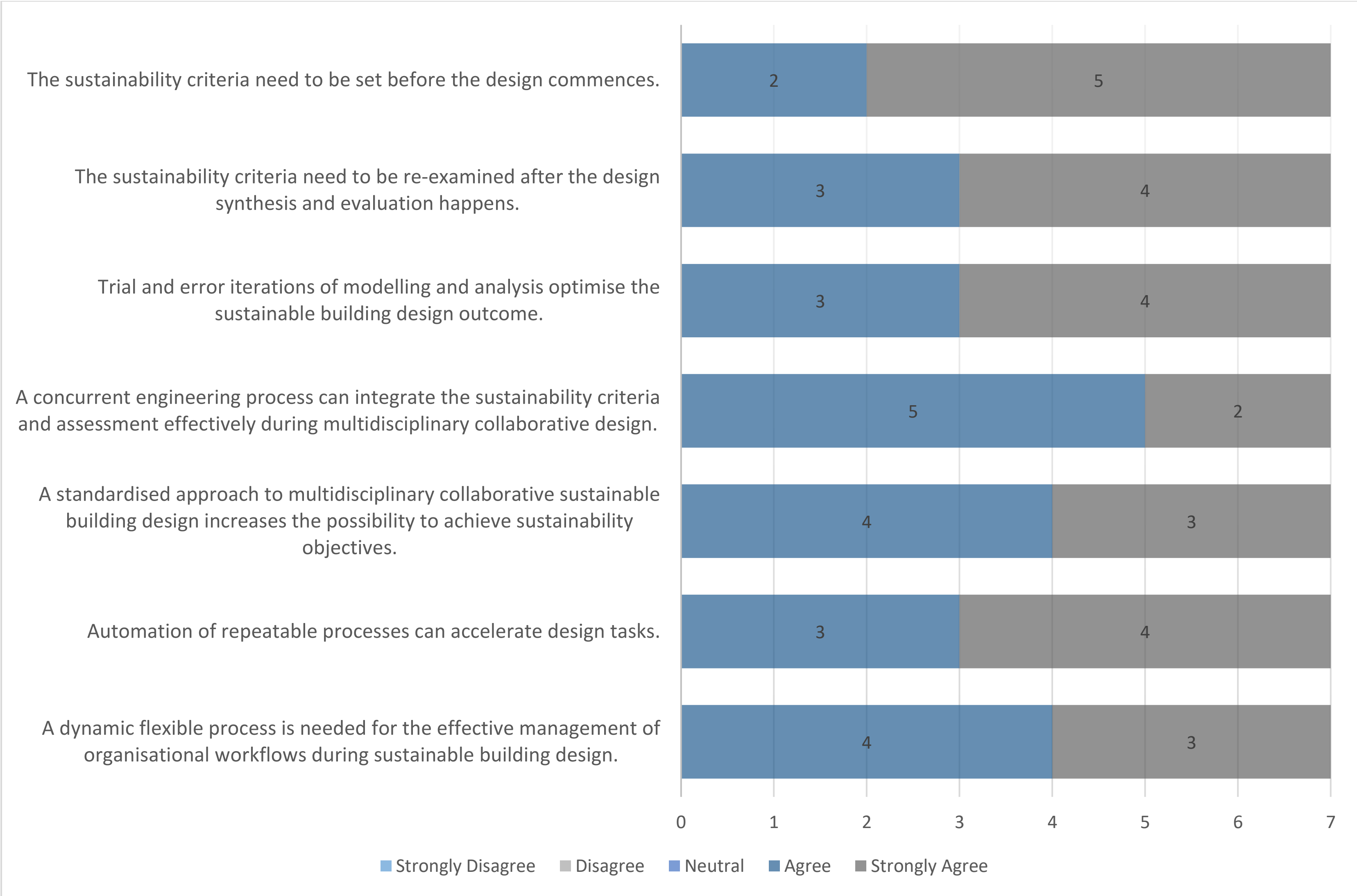


Figure 7.7 Industrial participants' attitudes towards a structured BIM-enabled sustainable design process

7.4.5. Adequacy and usefulness of the process model

There was consensus among the participants regarding the usefulness and feasibility of the process model for the implementation of collaborative SBD. A few quotes are presented below to demonstrate the nature of the feedback.

When Participant I-A was asked whether he found that the model captures the SBD process adequately, he enthusiastically replied the following: *"It definitely does. I like it. It is very useful and I'll use it myself. … It [SBD] is a complex process and the level of detail presented in the model is the most appropriate. You cannot represent it in a simpler way."*. Answering the same question, Participant I-B argued that: *"It is very well done, very comprehensive. I can recognise the process, it seems to be the type of way we approach things. …. It is very useful because you can ensure that every step of design is considered, at least. … It is good!"*. Participant I-C responded: *"Absolutely!"*, emphatically when asked the same question. He further added that: "*It is useful and easy to follow … good decomposition … the work is great!*". The response of Participant I-D also aligns with the above: *"It covers everything that should be there. The timing of considerations, sequencing of events, and terminology are very appropriate. … It is very useful and very new, novel. Most practitioners are not familiar with these concepts and process. … The model can provide useful guidance and clarify priorities between varying levels of expertise"*. Furthermore, Participant I-E responded: *"Yes, the model integrates trade-offs between design criteria … the level of detail is also very adequate … quite flexible to accommodate more performance criteria … [SBD] is a complex task, different performance criteria must be met at the same time. The model assists in guiding the process."*. Moreover, Participant I-F responded the following: *"It fills a big gap that exists in the industry. It is a basis for a good beginning … easy to follow and understand, if you are familiar with BIM and sustainability"*. Finally, Participant I-G stated that: *"It does. The system captures all important steps of holistic sustainable building design (climate analysis, passive, active design), and promotes coordination. … It is a useful framework that is easy to understand and implement … It can offer better control of the project and better team alignment … can potentially facilitate a continuous improvement process."*.

7.4.6. Suggestions for improvement of the process model

The model was presented directly to the practitioners accompanied by a description of the IDEF0 and IDEF3 nodes. All practitioners have reviewed the model as a whole before making any suggestions. As a result, the model has been amended based on the feedback received from the participants. This refinement has caused several additions and minor alterations to the model, which are discussed in this sub-Section and illustrated in Section 7.5 of this Chapter.

7.4.6.1. Level 1 decomposition

None of the participants suggested any changes to the IDEF0 Level 1 decomposition. In addition, function "*Undertake Strategic Definition*" (RIBA stage 0) has remained as-is with no alterations proposed by the participants.

7.4.6.2. Level 2 decompositions

Participant I-C suggested that alterations should be made in UOB 1 "*Prepare project brief*" by adding time-scales in order to *"avoid getting stack into a loop".* He also recommended that BIM Execution Planning (BEP) is an outcome of UOBs 1.1 to 1.4, and not a parallel activity. Table 7.9 illustrates the amendments to the model according to these comments.

Participant I-E recommended that the label of UOB 2.4 should be changed from "*Develop holistic concept*" to "*Optimise and refine concept*", which he considered to be a more suitable term for this function. He further recommended that the term "*Climate data*" should be amended to "*Climatic data*". Thus, the term has been substituted in both Level 2 and Level 3 UOB 2.1 decompositions.

7.4.6.3. Level 3 decompositions

Participant I-A commented that the task *"Perform CFD Analysis (wind &airflow)"* (UOB 2.4.9) should also be added in UOB 2.1 "*Develop building massing*", as part of the BPA. Furthermore, the participant argued that UOB 2.1.2 "*Estimate heating and cooling loads*" should be moved at the bottom of the sequence of parallel activities. Participant I-C claimed that the Level of Detail (LOD) is higher than the LOD100, included in the model from the beginning. He said that LOD200 and LOD300 is implemented from the start of design. However, the rest of the participants explicitly stated that the LOD suggested in the model is the most appropriate. Specifically, Participant I-A said that LOD200 should be changed to LOD100 (lower detail) in UOB 2.2. Since the majority of participants agreed that the LODs included in the model are the most appropriate, they have remained unchanged.

Participant I-A stressed the importance of re-defining internal condition types during concept design (RIBA stage 2), when the layouts and brief have been developed further. He recommended adding this function within UOB 2.2 "*Optimise fabric and layout*", where the passive design strategies are considered. Participants I-D and I-G also argued that thermal comfort should be re-examined at the end of each design iteration. Furthermore, Participant I-E talked about the need to re-examine the parameters that have to do with uncertainty of performance. He suggested that a UOB should be added in UOB 2.2, right after the architectural design is developed, and before the BPA takes place. He suggested that this function should be called *"Re-assess architectural programme".*

Participant I-E suggested that compliance with Building Regulations (e.g. Part L), in terms of performance, should be considered separately to the sustainability goals. This is because the regulations mandate specific inputs for the analysis of the credits that lead to the certification. However, these inputs may be unrealistic/irrelevant to the actual project programme and occupancy schedule of the building. The participant argued that this discrepancy has been documented as one of the reasons that cause the performance gap in buildings (Meacham et al., 2005; ARUP, 2013). He further recommended that "*Regulatory compliance*" should be a Call instead of a UOB (like the "*Client approval*" and "*Planning approval*" representations). He also suggested that this Call should be more general to accommodate both mandatory compliance (e.g. Part L, EPC) and ratings schemes (e.g. BREEAM, LEED, Passivhaus). A similar recommendation was made by Participant I-A; to substitute UOB 2.3.8 "*Assess Part L compliance*" with "*Assess EPC compliance*" so that the model can be applied to EU projects. Based on these recommendations, UOBs that consider compliance have been removed from the model, and the Call "*Regulatory compliance*" has been added into UOBs 2.2, 2.3, and 2.4 decompositions right after the BPA functions.

Participant I-A spotted several alterations to UOB 2.3 "*Configure mechanical services*" decomposition. First, he suggested that system optioneering and examination of main rootes precedes the sizing and configuration of HVAC systems. Secondly, he suggested that the LOD should be changed to LOD100 after UOB 2.3.4, and that the second LOD200 (after UOB 2.3.9) should remain unchanged. He also recommended that three functions should be added to the BPA's parallel tasks. These activities are: (i) UOB 2.3.9 "*Assess heating and cooling loads*", (ii) UOB 2.3.10 "*Place equipment",* and (iii) UOB 2.3.11 "*Perform cost estimation*".

Several participants also recommended a few minor alterations to the decomposition of UOB 2.4 "*Optimise and refine concept*". Participant I-A argued that shading should be re-examined once the architectural, structural, and MEP models have been coordinated (UOB 2.4.5). Participant I-G remarked that maintenance strategy should be examined again at this stage, along with the robustness of the structure and its materials. Therefore, three additional functions have been included in the IDEF3 model's description: (i) UOB 2.4.10 "*Perform shading analysis*", (ii) UOB 2.4.11 "*Develop maintenance strategy*", (iii) UOB 2.4.12 "*Assess robustness of structure and materials*". As discussed above, Participant I-E suggested to remove UOB 2.4.8 "*Perform BREEAM pre-assessment*" and substitute it with a Call for "*Regulatory compliance*", once the BPA tasks have been performed.

7.4.6.4. General recommendations

All participants explicitly expressed the opinion that they found the model to be very clear and well presented. Nevertheless, some of them made a few recommendations to improve the presentation of the research output. Participant I-C suggested that the colour-coding system should be explained more clearly in the description to avoid confusion. His first impression was that the colours were assigned merely for aesthetic reasons. Participant I-F said that a key next to each diagram would be helpful for novice practitioners to explain terminology such as the "*LOD*". Both Participants I-F and I-G claimed that a key, which explains the symbols, should be repeated next to each diagram's decomposition. They claimed that repeating the notations' symbols would bring more clarity to the diagrams.

7.4.7. GBB: Feasibility and enablers

There was consensus among the participants about the usefulness of GBB; a tool that facilitates the tracking of the SBD process presented to them. All participants agreed that they would use and/or recommend the use of GBB in the future. What is more, the participants made several recommendations regarding the capabilities and features that are missing from the existing OCPs, and would enable a BIM-enabled SBD process within a CDE. The key issues expressed are the following:

- Need for integration with BIM tools, such as Revit, for Level 3 BIM maturity (I-A).
- Integration with EnergyPlus software, and possibly, the automation of certain performance evaluation exercises such as sensitivity, or uncertainty analysis (I-E).
- Connection of the GBB tool with online databases for materials for quickest realisation of the proposed design (I-G).
- Suggestion to integrate GBB with an existing platform for collaboration (such as 4Projects), or with an existing project management tool (like the NBS BIM toolkit) so as to avoid duplication (I-C).
- Need to visualise, and review, the day-to-day progress of the design process at each stage and assess it against specific criteria by applying a scoring system (I-B).
- Reporting should also be included in the SBD process along with triggers that track its progress, which are useful for coordination of design tasks (I-C).
- Compliance checking against building regulations was also discussed, although the participant recognised that this is a challenging task due to the amount and variety of those (I-B).
- Concern regarding privacy issues was expressed; the information shared within a CDE should require specified permissions that enable access only to authorised team members (I-B).

7.5. Amended IDEF process model and definitions

This Section presents the final process model (Levels 1 to 3), amended according to the recommendations made during industry validation. Figure 7.8 illustrates the IDEF model's master-map, which consists of three level hierarchies. Level 1 represents the high-level IDEF0 process model decomposition aligning with the RIBA's (2013) hard decision gates, and colour-coded accordingly. Level 2 contains the decompositions (sub-processes) of the Level 1 process. Level 3 contains the decompositions of the Level 2 processes. Levels 2, 3, and 4 (IDEF3) provide granularity that demonstrates which functions are performed by each role, parallel activities, and soft-gates. The complete IDEF process model (before the final refinements) can be found in Appendix D (Levels 1-4).

Table 7.9 contains the highest three levels of IDEF decomposition diagrams (presented during the validation), and Table 7.10 the inputs and outputs of each UOB. The diagrams provide a simplified description of the relationships between BIM-enabled sustainability functions (as UOBs), and the gateways (as Junctions) for the iteration cycles of the SBD collaborative process. The inputs (information required) and outputs (information shared) of the functions are illustrated as Objects. The Objects' states (e.g. Initial, Optimised, Approved, Shared) change as they are altered by the functions.

7.5.1. Stage 0: Strategic Definition - NEED

The Level 2 decomposition of UOB 0 "*Undertake Strategic Definition*" (see Table 7.9) requires the inputs shown in the Level 1 hierarchy model, which are the Plain English Questions, Occupants' Needs, Environmental Impact, and Client's Aspirations. Then, UOBs 0.1, 0.2, 0.3, and 0.4 (and their sub-processes) are performed in parallel. The output of this function is the Strategic Brief, which includes the Employer's Information Requirements (EIR), Team Appointments, Project Objectives (e.g. BREEAM, Passivhaus), and Sustainability Aspirations (e.g. daylight performance, embodied carbon, renewable sources).

7.5.2. Stage 1: Preparation and Brief - EXECUTION

UOB 1 "*Prepare Project Brief*" (see Table 7.9) requires the outputs of UOB 0 as inputs. The main activities that need to take place during this stage are the development of a BEP and Schedule of Services (UOBs 1.5 and 1.3), based on the information contained in the EIR. When EIR are not provided by the Client, it is the Project Lead/Lead Designer's responsibility to form a BEP that states the sustainability targets and implementation strategies, and communicate it with the rest of the design team. Furthermore, the Sustainability Objectives and Benchmarks/Metrics need to be clarified at this point to achieve design team alignment (UOBs 1.1 and 1.2). Then, the decisions and commitments made should be compiled into the Initial Project Brief.

7.5.3. Stage 2: Concept Design - DELIVERY

Once the requirements definition phase is completed (at RIBA stage 1), the climatic data, occupancy requirements, and site and topography information are available. The Interviewees described RIBA stage 2 as a process that is divided into four phases of design and assessment loops: (i) building massing; (ii) fabric and layout optimisation; (iii) mechanical systems configuration; and (iv) simultaneous optimisation of building envelope and mechanical services. The functions (UOBs 2.0, 2.1, 2.2, 2.3, and 2.4) of the Level 2 hierarchy decomposition of UOB 2 "*Develop Concept Design*", follow this structure (see Table 7.9). Furthermore, Table 7.11 synthesises the findings from the interviews (structured and unstructured descriptions) and an extensive literature review survey in order to define the BIM-enabled tasks for SBD (as UOBs). Each UOB is defined by the WHY (intent, sustainability aspirations), WHO (role, competencies/training, collaborators), WHAT (information requirements, inputs-outputs), and HOW (creation/processing, software tools, communication methods).

UOB 2.0 "*Perform climate and weather analysis*" is a critical step of SBD that examines parameters such as temperature ranges, and precipitation. The aim of this task is to identify the appropriate design strategies that can be implemented for a specific location. During this analysis, the Sustainability Engineer generates weather data diagrams (e.g. temperature, humidity, solar radiation, wind roses) and interprets the results using methods such as the psychrometric chart (including comfort zones) to determine the most efficient design strategies for the site. The weather data files are obtained, and used for BPA, either directly from weather stations (e.g. US Department of Energy), or they are merged using specialised software (e.g. Meteonorm) for more accuracy. The user imports the Climatic Data file in the software (e.g. Climate Consultant, IES-VE, or Sefaira) and selects the Comfort Zone model of their preference (e.g. Adaptive Comfort Model in ASHRAE Standard 55-2013) (Olesen and Brager, 2004; ANSI/ASHRAE, 2014). Level 2 UOBs of concept design stage (2.1, 2.2, 2.3, and 2.4) have been further decomposed to Level 3 hierarchy (see Table 7.9), and their information requirements are described in Table 7.10.

UOB 2.1 "*Develop building massing*" refers to the perception of the general shape, form, and size of the building. For SBD, orientation and location on site are also important considerations for the adoption of passive design strategies such as daylighting and natural ventilation. The energy efficiency of those strategies is assessed by calculating the heating and cooling loads, aiming to reduce them as much as possible. For this reason, a series of analyses must take place (UOBs 2.1.1-2.1.6) before committing to design decisions. If the Architects are not able to perform BPA themselves, they would need to work closely with a Sustainability Engineer who can provide advice. The iterative loop of design and assessment continues until the Architect, Sustainability Engineer, and Client reach an agreement (J4). The output of UOB 2.1 is a generic representation, LOD100 building mass 3D model, which contains indicative height, volume, location, and orientation (BIM Arch LOD100).

UOB 2.2 "*Optimise fabric and layout*" is concerned with optimising the fabric performance by utilising passive design strategies (e.g. daylight, solar gains, natural ventilation, thermal mass and night cooling). The objectives of this task are to save energy and cut billing costs, while increasing comfort for building occupants. Building materials (e.g. roofs, walls, windows, doors, and floors) need to be carefully selected based on criteria such as thermal performance, and carbon footprint. Furthermore, the building is divided in the thermal zones, which are the unit of analysis for performance evaluation simulations. Each thermal zone is defined by the occupancy requirements and operation schedule that vary depending on the function of each space. The iterative loop (design-assessment) continues until the Architect, Sustainability Engineer, Structural Engineer, and Client reach an agreement (J8).

UOB 2.3 "*Configure mechanical services*" examines system comparison and selection, along with planning of sustainable active design strategies. Once the architectural, structural, and mechanical BIMs are developed, they should be coordinated utilising appropriate software (e.g. Navisworks, Solibri) in order to identify and resolve design clashes. The output of UOB 2.3 is a coordinated LOD200 BIM that consists of generic placeholders graphically represented as a generic system, object, or assembly with information attached.

UOB 2.4 "*Optimise and refine concept*" entails the optimisation of the concept by examining the trade-offs between design elements in more detail (UOBs 2.4.6-2.4.13). Here, the Client, Architect, MEP Engineer, Structural Engineer, Sustainability Engineer, and Cost Consultant/Contractor should work collectively until the design criteria are met (J17).

7.5.4. Critical decision points and benchmarks (Junctions)

The identification of decision points is discussed in PAS1192:2-2013 (BSI, 2013b) as a critical aspect of the BIM process. Decision points in phase-gate review comprise two types of gates; hard-gates when the design freezes until the review is conducted, and soft-gates that allow the project to proceed in parallel, thus enabling a CE approach to SBD. On one hand, hard-gates serve the purpose of committing to decisions collectively. On the other hand, in a CE design approach, soft-gates are identified throughout the process so as the decision making points occur in parallel. The benefit of implementing soft phase-gate reviews is that the project is allowed to proceed in parallel with conducting the review. In order to achieve sustainability objectives, design strategies are implemented and assessed towards a set of criteria and benchmarks. The timing when these decisions take place is crucial for achieving sustainability, since once commitments have been made early in the process, it is more costly to repeat the work that has already been done. To achieve that, the right information should be delivered to the right people at the right time. This practice presents the biggest challenge for achieving sustainability without increasing cost and causing delays in the project programme. Identifying critical decision points assists in determining the loops of an iterative design process. A mapped process that can be audited, along with soft-gates and hard-gates for SBD, would provide quality assurance that the sustainability objectives would be met.

The IDEF3 model's Junctions serve the purpose of providing soft-gates in the process of integrating sustainability considerations and criteria at the right time. Table 7.12 includes the performance criteria identified from the incidents' narratives aligned with the Junctions of the IDEF3 decomposition. Junctions J1 and J11 of UOB 2 "*Develop concept design*" correspond to the Client Approval decision gates. The Client bases their decision on subjective preferences (e.g. aesthetics, aspirations). For this reason, the criteria cannot be made explicit for these decision points. The "*Exclusive-OR*" Junctions [X] correspond to decision points in the process, when the process may iterate. In UOB 2.1 decomposition, the synchronous (e.g. J3) and asynchronous (e.g. J2) "*AND*" Junctions [&] mean that by the end of task "*Build massing model*" (UOB 2.1.1), functions (UOBs) 2.1.2 to 2.1.6 may begin, but not necessarily at the same time, while once they are all completed, they are part of the "*Massing assessment report*" in PDF format. Junction J4 corresponds to the sustainability criteria shown in Table 7.12 (4.1 and 4.2) and the agreement between the Client and the Architect before moving to the next phase of design (UOB 2.2). Junction J8 involves the agreement of the Client, the Architect, and the Sustainability Engineer regarding the sustainability criteria 8.1 to 8.10. Junction J10 requires the consensus between the Client, MEP Engineer, and the Sustainability Engineer regarding the "*Services assessment report*" in PDF format. The sustainability criteria contained in the report, include the rows 10.1 to 10.5 of Table 7.12. Junctions' J12 and J14 iterations correspond to the event that the Arch, Struct, and MEP BIMs are not coordinated. In that case, amendments should be made to resolve the issues. Junction's J17 criteria involve a holistic trade-off among every sustainability issue considered in the previous Junctions, as well as setting the targets for criteria 17.1 to 17.8 of Table 7.12. These are based on the 3D models, 2D drawings, the "*Holistic sustainability report*", and the "*Cost estimation report*". The Client, Architect, Structural Engineer, MEP Engineer, Cost Estimator, and Contractor may also be involved in this decision point. Table 7.12 contains example benchmarks of the sustainability criteria for office buildings. Nevertheless, it should be noted that the sustainability benchmarks vary among different types of buildings such as schools (CIBSE, 2015), healthcare, or multi-residential (BREEAM, 2014). Although the tasks' sequences have been found to follow similar workflow patterns, for a variety of building types (e.g. schools, higher education, healthcare, and offices), the design criteria and priorities, vary among different cases.

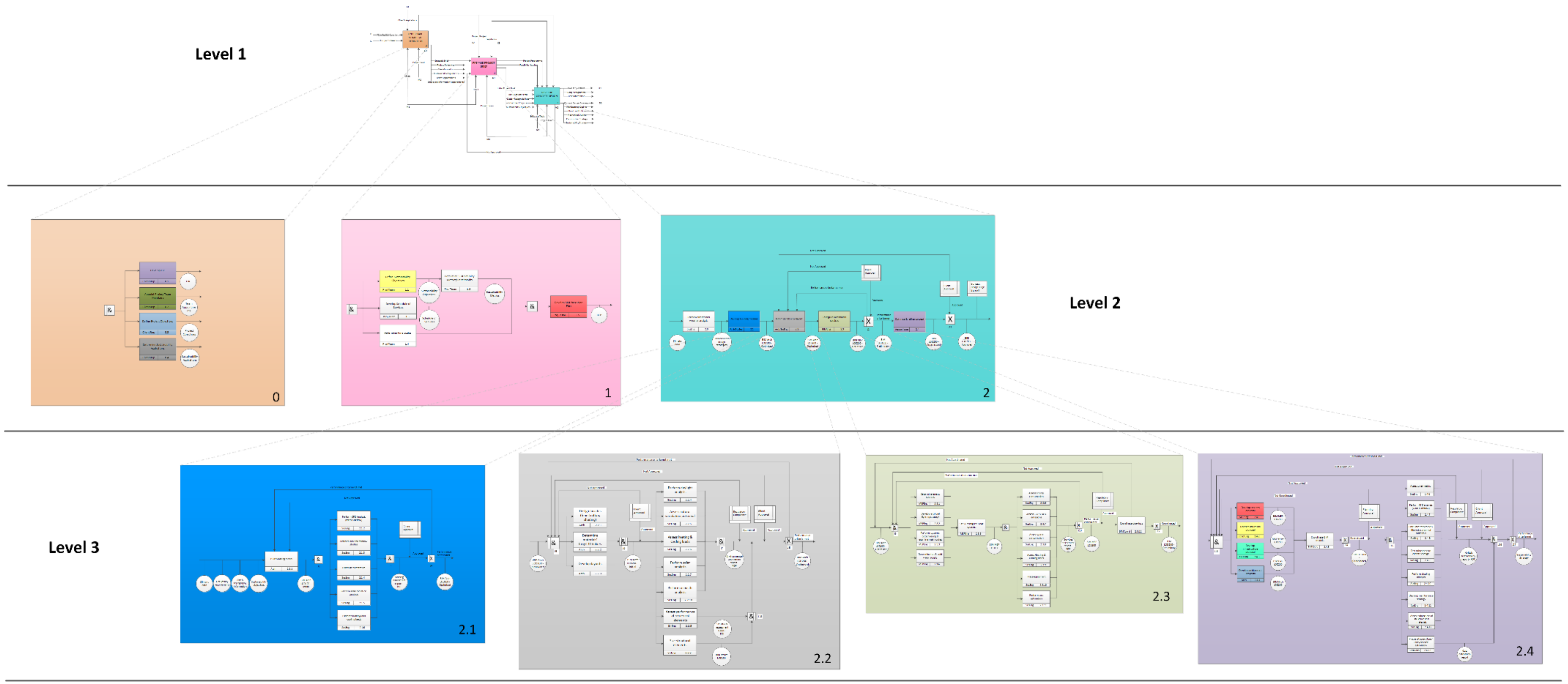
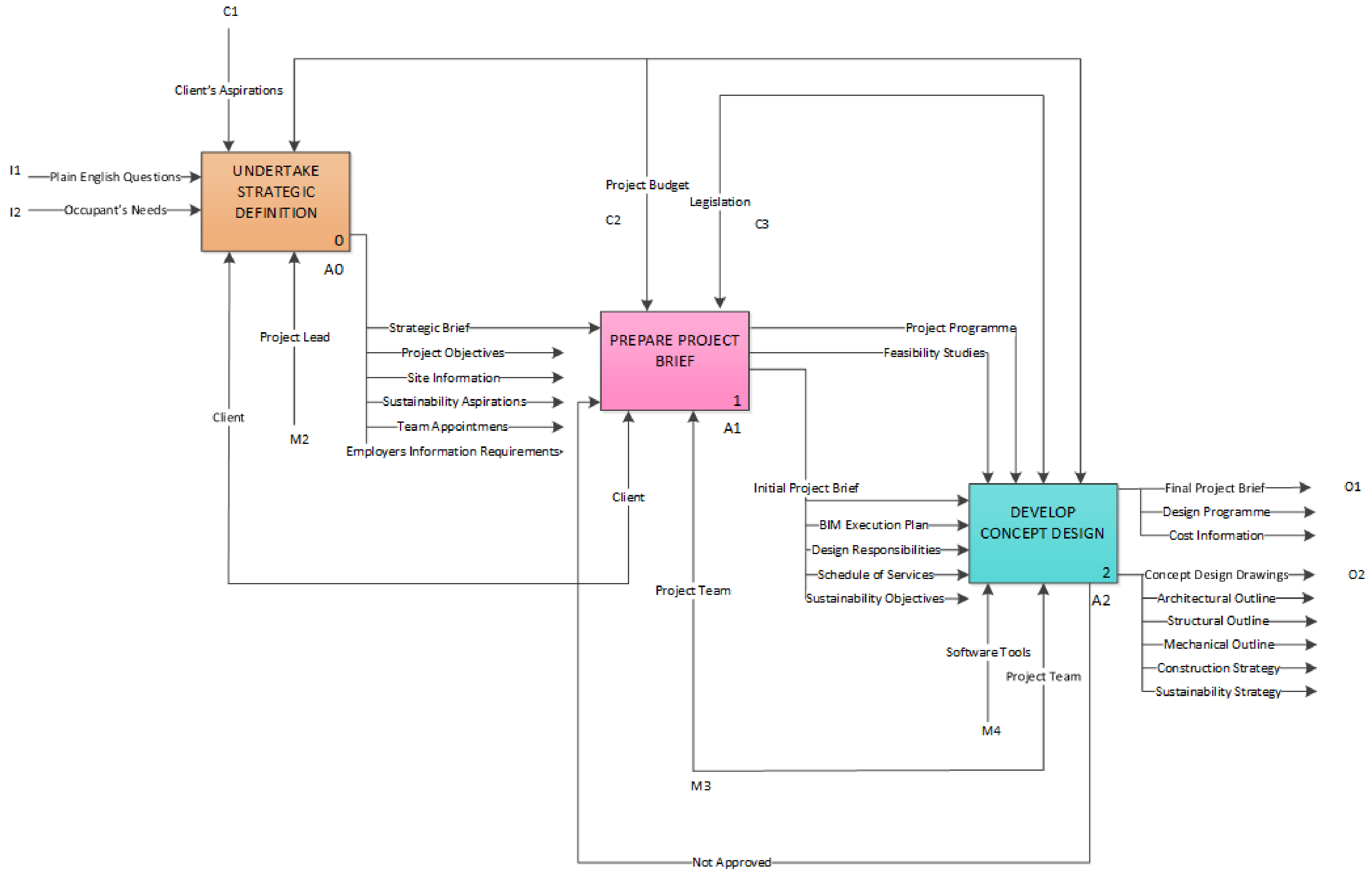
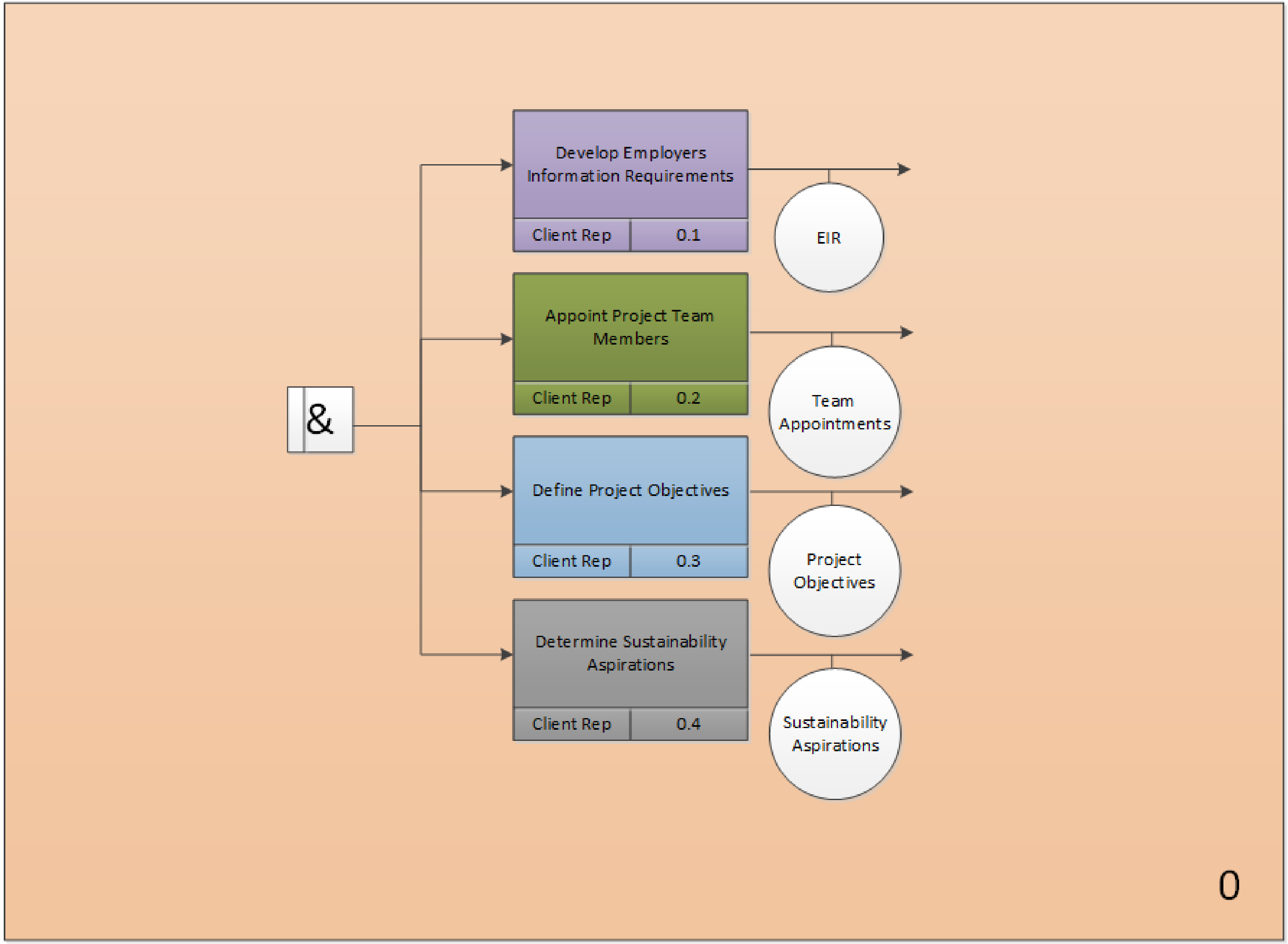
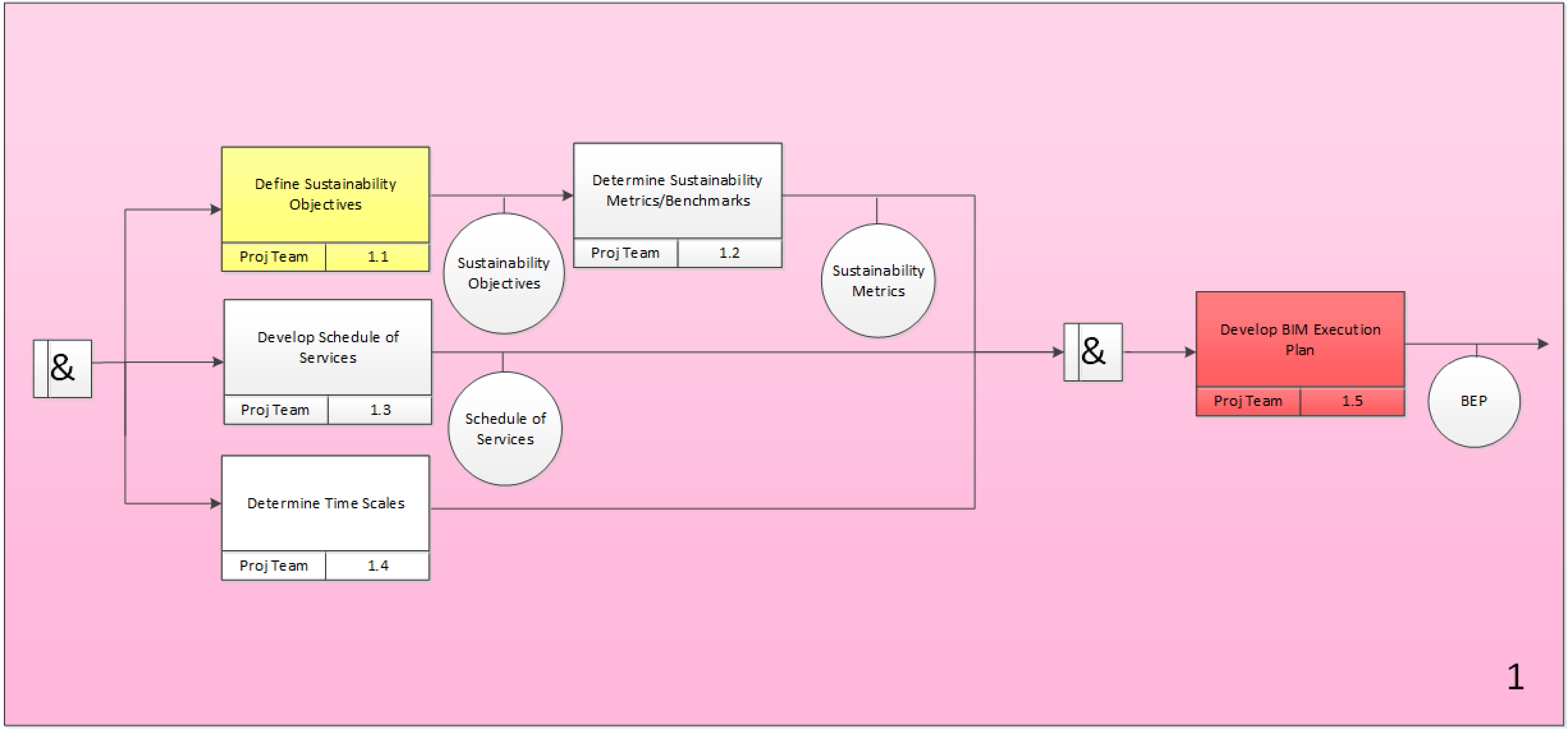


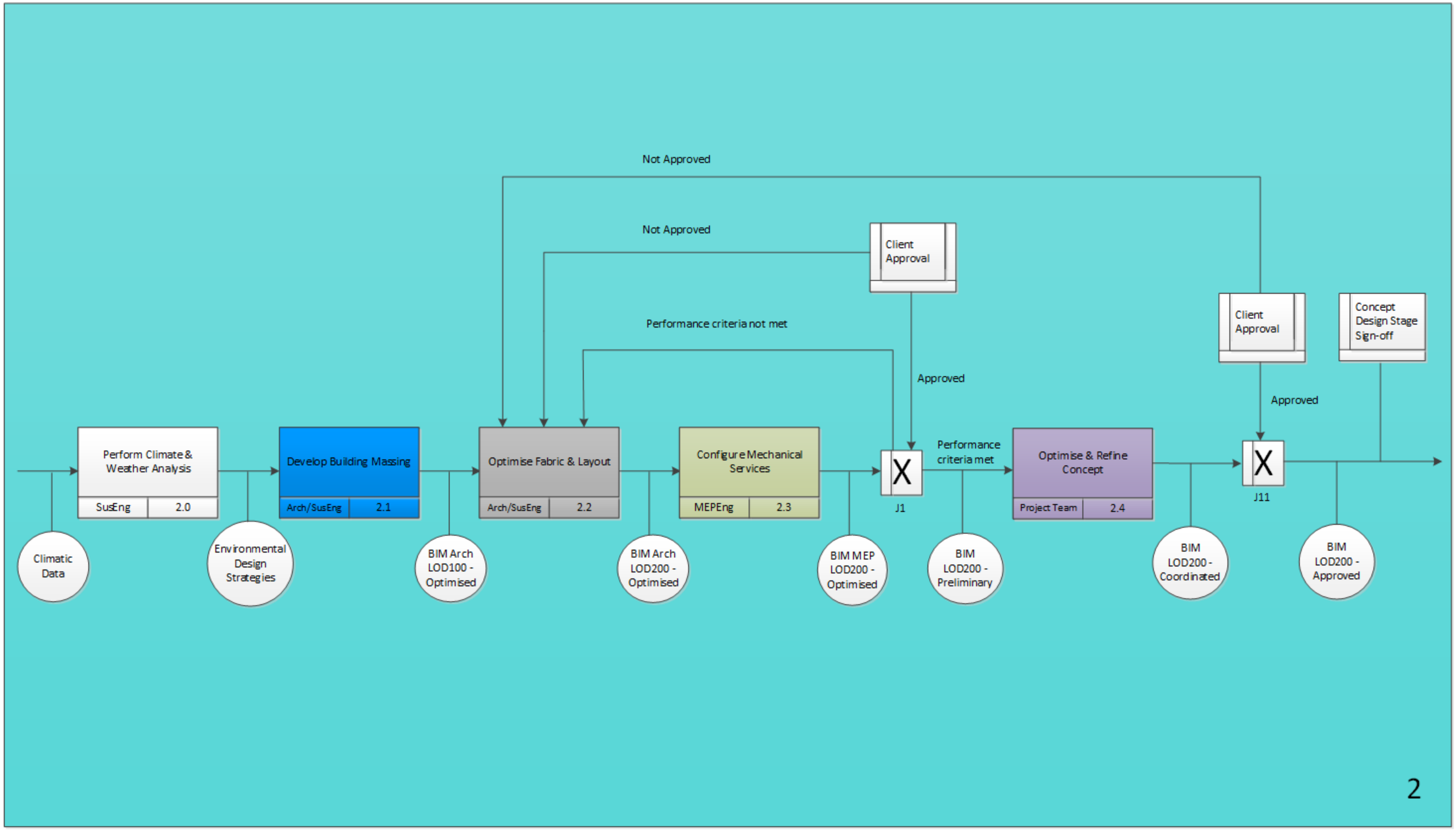
Figure 7.8 IDEF process model's master-map showing hierarchical relationships between processes and sub-processes

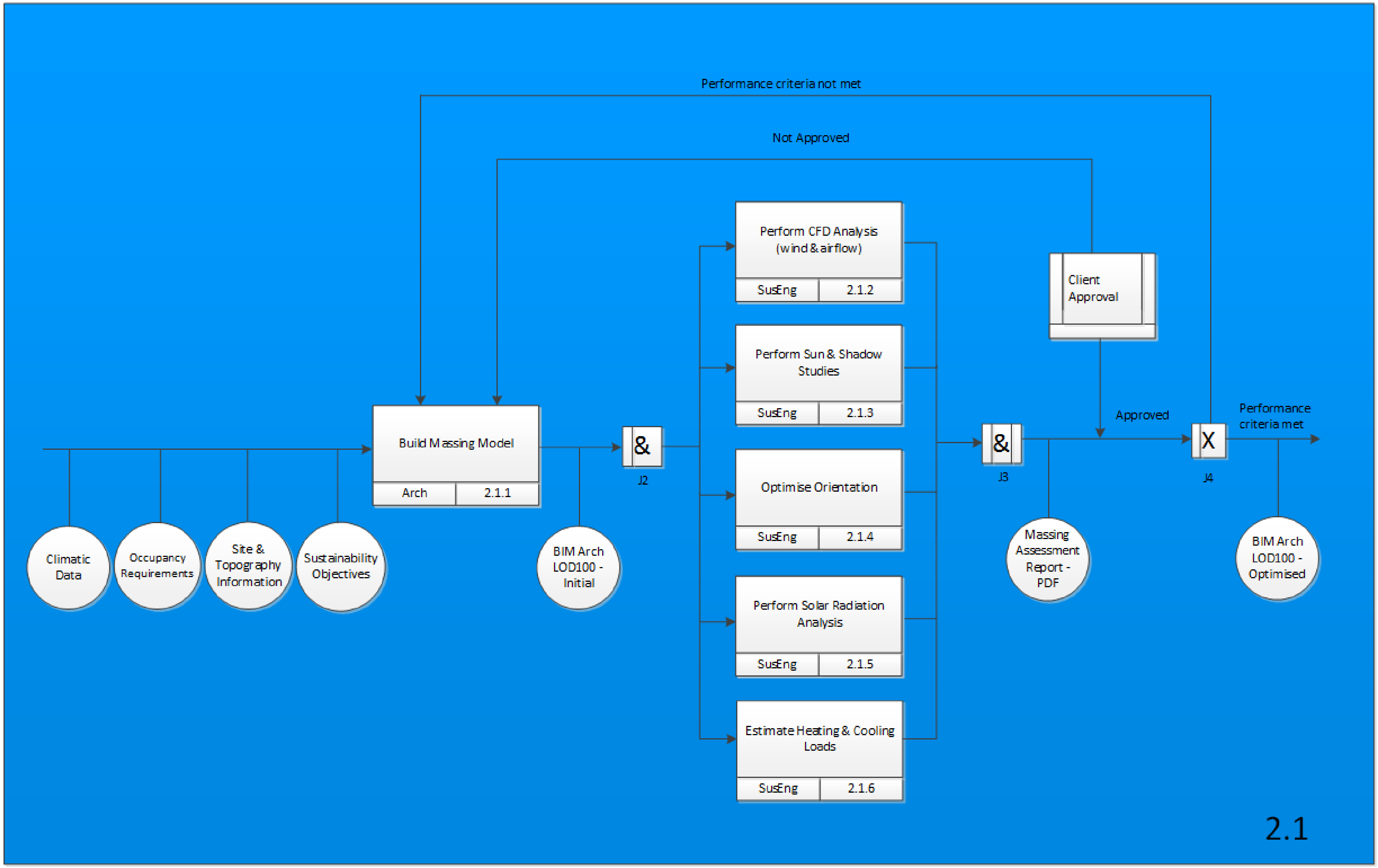
Table 7.9 IDEF decomposition diagrams

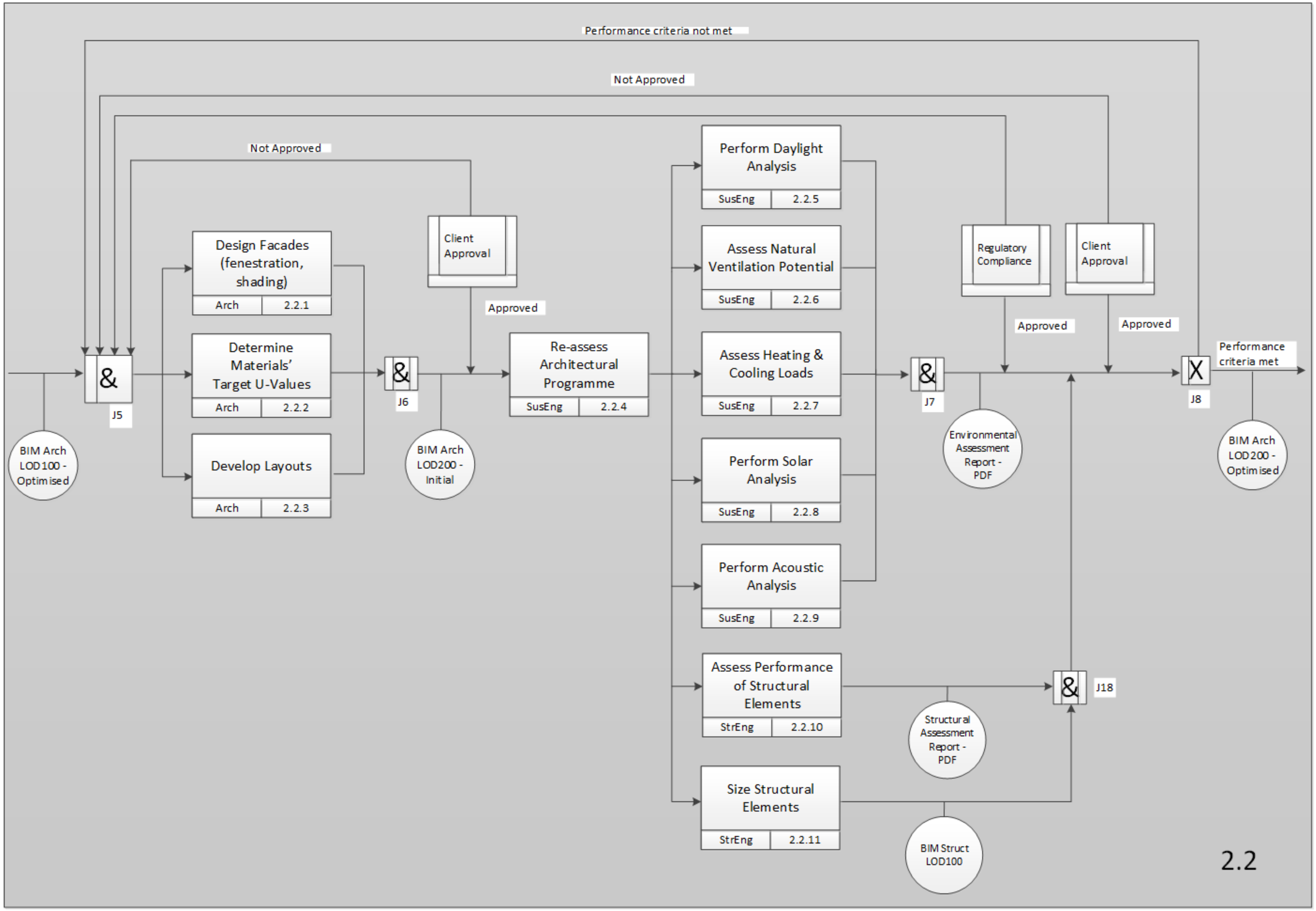
Hierarchical Level	IDEF Process Decomposition Diagram
Level 1	

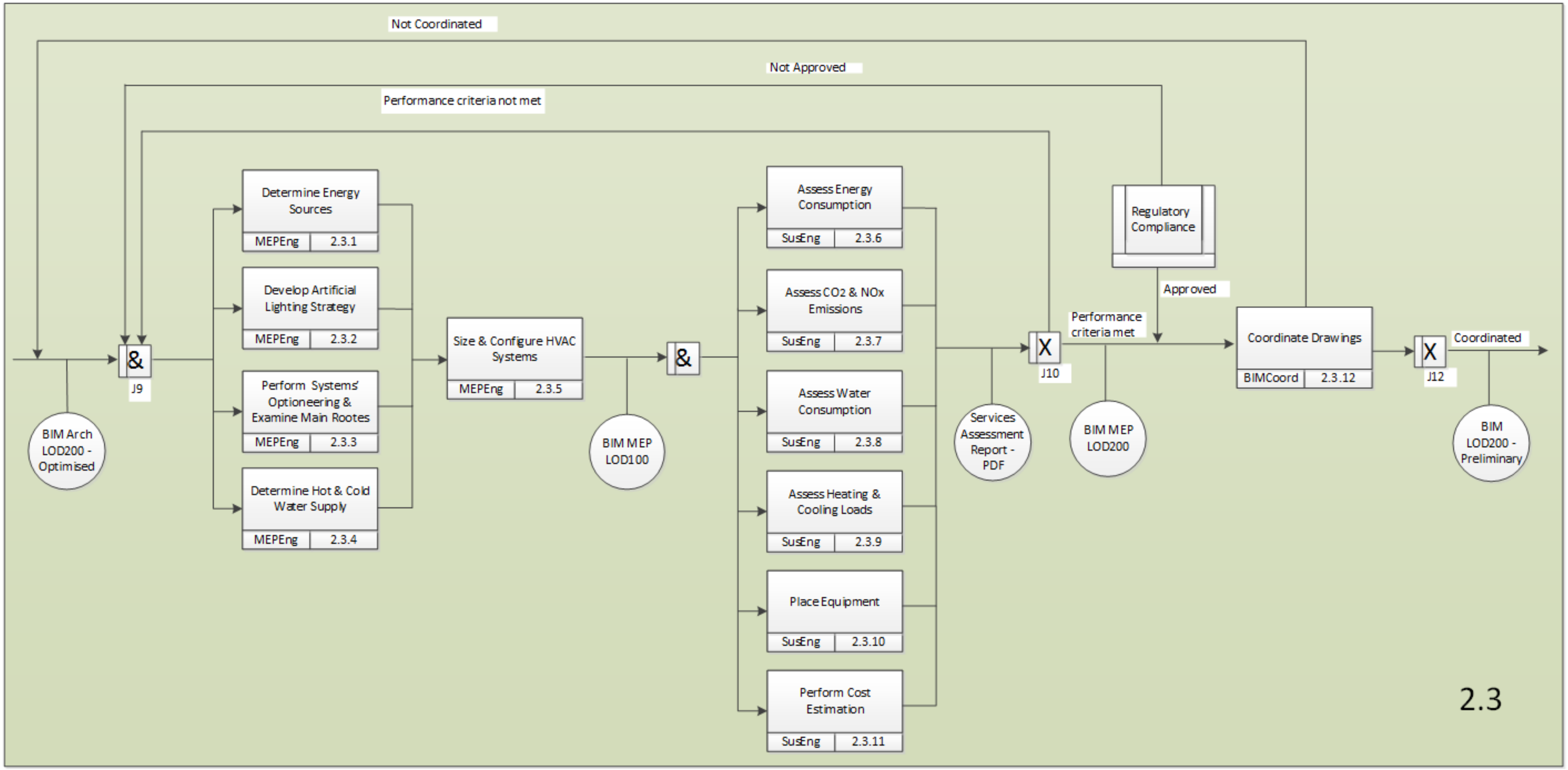
Hierarchical Level	IDEF Process Decomposition Diagram
Level 2	

Hierarchical Level	IDEF Process Decomposition Diagram
Level 2	

Hierarchical Level	IDEF Process Decomposition Diagram
Level 2	

Hierarchical Level	IDEF Process Decomposition Diagram
Level 3	

Hierarchical Level	IDEF Process Decomposition Diagram
Level 3	

Hierarchical Level	IDEF Process Decomposition Diagram
Level 3	

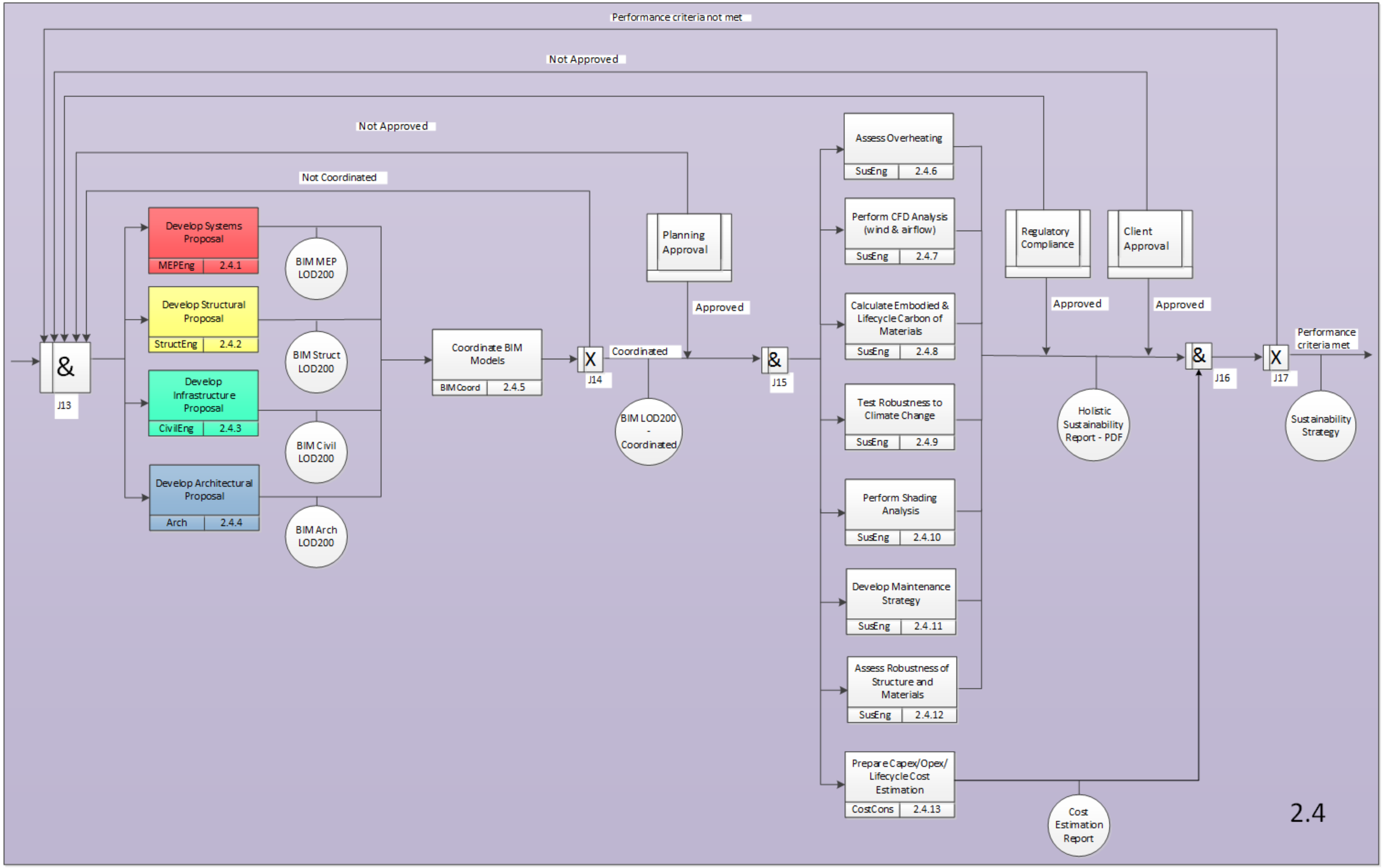
Hierarchical Level	IDEF Process Decomposition Diagram
Level 3	

Table 7.10 Information Requirements of UOBs (Table 7.9 decomposition diagrams)

Information Requirements (IR)

Level 1 Decomposition

<u>Inputs of UOB 0</u>

- Plain English Questions (see Chapter 5, Section 5.2.3)
- Occupants' needs (e.g. comfort and health): activities, functions, number of people, equipment, personal preferences, acoustic requirements, identification of air pollutants (such as nitrogen oxides (NOx), Volatile Organic Compounds (VOCs), and respirable particulate matter), and water contamination.
- Environmental impact: location, topography and surroundings, materials' availability, energy sources, water availability, ecology, risk of flood.
- Client satisfaction: UK Level 2 BIM maturity, Government Soft Landings (GSL), Building Regulations (e.g. Part L, EPC), certification assessment scheme (e.g. BREEAM, LEED, Passivhaus), budget allowance, timeframe.

<u>Outputs of UOB 2</u>

- Final Project Brief
- Design Programme
- Cost Information
- Concept Design Drawings
- Architectural Outline
- Structural Outline
- Mechanical Outline
- Construction Strategy
- Sustainability Strategy

Level 2 Decomposition

<u>Outputs of UOB 0</u>

- Strategic Brief
- Employers Information Requirements (EIR): managerial, commercial, technical
- Team Appointments: Architect/Lead Designer, Landscape Architect/Ecologist, MEP Engineer, Structural Engineer, Civil Engineer, Geotechnical Engineer, Transport Consultant, Cost Consultant, Contractor, Sustainability Lead/Consultant, Sustainability Engineer, Energy Modeller, Lighting Engineer, BREEAM/Passivhaus Assessor, Acoustician, Public Health Consultant, BIM Manager/Coordinator.
- Project Objectives: BREEAM, Passivhaus, overheating, Construction Design Management (CDM), Client approval, function, insurance, UK building regulations, Planning and Heritage, lifecycle cost, local sourcing.
- Sustainability Aspirations: low embodied carbon and material reuse, energy use and renewable sources, greenhouse gas emissions, daylight performance and efficient solar shading, natural ventilation, robustness to climate change, innovation, functionality and flexibility, disabled access, thermal mass.

Level 2 Decomposition

<u>Outputs of UOB 1</u>

- BIM Execution Plan (BEP): description of the project, project directory, contractual tree, design responsibility matrix and information exchanges, project programme, technology strategy (software, hardware, and training), communication strategy (i.e. meetings, types of meetings, queries, data exchanges, format, and transfer mechanisms), common standards, CAD/BIM manual (i.e. coordination strategy, standards, coordination, collaborative process, reviews and quality control), and change control procedures.
- Schedule of Services
- Sustainability Objectives
- Sustainability Metrics
- Feasibility Studies
- Initial Project Brief

Information Requirements (IR)
Level 3 Decomposition <u>Inputs of UOB 2.0</u> • Location: latitude, longitude • Orientation: magnetic declination • Sun angle: clock time azimuth and altitude • Insolation: direct and diffuse solar radiation in Kilowatt-hours per square meter (KWh/m²), cloud cover (%), solar radiation diagrams • Temperature: average minimum, average maximum in Celsius (°C) • Rainfall/precipitation: millimetres (mm) • Relative Humidity: per cent (%) based on dew point • Wind analysis: speed in meters per second (m/s), direction (degrees) and frequency for each month or season <u>Outputs of UOB 2.0</u> • Psychrometric Chart illustrating comfort zones • Design Guidelines of passive design strategies
Level 3 Decomposition <u>Inputs of UOBs 2.1.1-2.1.6</u> • Schedule: number of people, days of occupancy per month, hours a day of occupancy, type of activity per room (thermal zone) • Thermal analysis: comfort zone (air temperature, air velocity, humidity) mean radiant temperature, heat balance model, comfort equations, adaptive theory principle • Climatic data: sun angle, temperature (°C), diffuse and direct solar radiation (KWh/m²), rainfall (mm), humidity (%), wind speed (m/s) and direction (degrees) <u>Outputs of UOB 2.1.1/ Inputs of UOBs 2.1.2-2.1.6</u> • Massing: rotation of orientation and analysis of building forms • Properties: insulation (R-Value, U-Value) <u>Outputs of UOBs 2.1.2-2.16</u> • Heating and cooling loads: Kilowatt-hours per square meter (KWh/m²) • Cast shadows for selected hour ranges at specific days of the year (typically solstices and equinoxes) • Diagram of heating and cooling loads for building rotations (0 to 90 degrees) • Insolation values (KWh/m²) on selected planes (e.g. walls, roofs, site) for specified time periods
Level 3 Decomposition <u>Outputs of UOBs 2.2.1-2.2.4</u> • Climatic data: sun angle, temperature (°C), diffuse and direct solar radiation (KWh/m²), rainfall (mm), humidity (%), wind speed (m/s) and direction (degrees) • Site analysis: site elements and qualities, topography, surroundings (e.g. masses, materials) • Schedule: number of people, days of occupancy per month, hours a day of occupancy, type of activity per room (thermal zone) • Thermal analysis: comfort zone (air temperature, air velocity, humidity) mean radiant temperature, heat balance model, comfort equations, adaptive theory principle • Sound: decibel (dB) levels and quality vary per room requirements, environmental noise prevention and elimination • Massing: rotation of orientation and analysis of building forms • Materials: embodied energy/carbon, lifecycle carbon analysis, toxicity • Elements' properties (walls, ceilings, floors, roofs, partitions): insulation (R-Value/U-Value), thermal lag (hours), solar absorption (0-1), colour reflection (0-1), emissivity • Glazing: size, location, shape, U-Value, G-Value, SHGC (Solar Heat Gain Coefficient), VLT (Visual Light Transmittance), LSG (Light to Solar Gain Ratio), shading coefficient (0-1), transparency, emissivity (0-1), colour reflection

Information Requirements (IR)
<u>Outputs of UOBs 2.2.5 - 2.2.11</u> • Daylighting analysis: Daylight Factor (DF) percentage (%), overshadowing, Daylight Autonomy (DA) percentage (%), solar shading control or illuminance pattern, glare, visibility, reflections • Natural ventilation: CFD (Computational Fluid Dynamics) analysis, mean wind velocity (m/s), atmospheric boundary layer (height), turbulence, infiltration (air leakage), indoor air quality • Heating and Cooling loads (KWh/m^2) • Insolation values ($KWh/m^2/day$) on selected planes (e.g. walls, roofs, site), overheating, passive solar heat • Structural analysis: frame sizing, windows and doors bracings, embodied carbon, and thermal mass/lag (hours) of structural materials • Sound analysis: wave analysis, Initial Time Delay Gap (ITDG), Reverberation Time (RT), Early Decay Time (EDT), sound rays distribution (uniformity)
Level 3 Decomposition <u>Outputs of UOBs 2.3.1 – 2.3.5</u> • Geometry: plant(s) location(s) and sizing, ducts' location and routes • Renewable systems: average daily output, energy losses • Lighting: Correlated Colour Temperature (CCT) in Kelvin (K), Colour Rendering Index (CRI), colour constancy, uniformity, diversity, luminous efficacy (lumens per watt), luminaire, lamps (photometrics), Part L (W/m^2 per 100 lux loads), Watts per square meter (W/m^2 per 100 lux loads), controls • Heating and cooling: HVAC (heating, ventilation, and air conditioning), convection heat, radiant heat, radiant cooling, convection cooling, exergy, heat pumps, electric heating, Gas/oil/LPG (Liquid Petroleum Gas) fired indirect systems (boilers), Combined Heat and Power (CHP), Coefficient Of Performance (COP), latent loads • Ventilation: mechanical or hybrid volumetric flow in cubic meters per second (m^3/s), mass flow (Kg/s), fresh air ventilation requirement (air changes per hour), ventilation rate, air quality, energy recovery, air filtration, ventilation effectiveness (ve) • Water: Domestic Hot Water (DHW), hot and cold water (l/person), resistance flow, pumps, sterilisation, water harvesting, efficient equipment, greywater reuse, onsite water treatment, schedules, commission, operation and maintenance <u>Outputs of UOBs 2.3.6 – 2.3.12</u> • Energy consumption ($Wh/m^2/yr$) for heating, cold water, electrical load, IT (Information Technology) and small power • Carbon emissions ($CO_2/m^2/yr$) • Part L compliance (2013, 2016, 2019), Display Energy Certificate (DEC) rating (A, B, C, D) • Water consumption ($m^3/person/yr$) • Coordinated LOD200 BIM and information requirements
Level 3 Decomposition <u>Inputs of UOB 2.4</u> UOB's 2.3 Outputs <u>Outputs of UOB 2.4.13</u> • Capital expenditures (CapEx): overall construction, material cost, components cost • Operating expenses (OpEx): operational cost, energy cost, energy savings • Lifecycle cost: Standardised Method of Life Cycle Costing (RICS)

Table 7.11 Delivery of information during RIBA stage 2 (Concept Design)

UOB	*WHY*	*WHO*	*WHAT*	*HOW*
Perform climate and weather analysis (UOB 2.0)	Climatic conditions are critical for building performance analysis. Analysing the local climate results in identifying the appropriate design strategies that can be implemented for a specific location.	This role needs to have the ability to understand weather data diagrams (e.g. temperature, humidity, solar radiation, wind roses) and interpret the results presented in a psychrometric chart (comfort zones) to determine the most appropriate design strategies for the site. This task is undertaken by the Sustainability Engineer, or the Sustainability Consultant.	Weather data comes from physical weather stations, which are situated at large airports and are less accurate. Such weather files can be downloaded from the US Department of Energy (DOE) and "Climate.One Building" (2014-2016). More accurate data can be generated by Meteonorm software, which combines data from various weather stations that surround the site. The output of this analysis is the passive design strategies (Design Guidelines) that can be implemented to extend the comfort zones within the building.	Open-source software is available for this purpose (e.g. Climate Consultant). Furthermore, several BPA software offers these capabilities such as IES-VE, Sefaira, and EcoDesigner. The user imports the Climatic Data file in the software, selects the Comfort Zone model of their preference (e.g. ASHRAE Standard 55 and Current Handbook of Fundamentals Model, ASHRAE Handbook of Fundamentals Comfort Model up through 2005, Adaptive Comfort Model in ASHRAE Standard 55-2013), and the Passive Design Strategies that are to be examined.
Develop building massing (UOB 2.1)	Massing of the building is deciding the size and shape (e.g. height, footprint). The target is to minimise energy requirements by reducing the heating and cooling loads required while maximising passive cooling (natural ventilation), passive heating (direct solar radiation), and daylight (diffuse solar radiation). The shape, orientation, and location of the building on site are the critical decisions of this task. Sun and shadow studies (UOB 2.1.3) reveal the availability of daylight, and the impact of topography and surrounding buildings. Also, the Rights to Light Act (1959) needs to be considered. The building height needs to cause minimal disruption to the surrounding buildings and comply with the Local Authorities requirements (UOB 2.1.1). Solar radiation analysis (UOB 2.1.5) determines the availability of sun beams that can be utilised for passive heating strategies and renewable energy generation (e.g. photovoltaics).	This responsibility is undertaken by the Architect, who is responsible for the design development. In order to perform this task, they need to have an understanding of the sustainability principles (e.g. heuristics, rules of thumb) so as to potentially achieve fewer iterations. Manipulation of 3D authoring tools, and the ability to interpret the environmental analysis results are also required. An in-house Sustainability specialist could perform the BPA at this stage. If such a specialist is not a part of the architectural design team, they would need to work closely with a Sustainability Consultant or a Sustainability Engineer who can provide advice.	The climatic data, occupancy schedule and comfort levels, site location and topography, and the sustainability metrics need to be available before initiating building the massing model. In the case of an informed Architect, the output is an optimised building mass 3D model. If a Sustainability Engineer is required, PDF reports are provided to the Architect until both parties, along with the Client, reach an agreement (J4).	Building massing can be done in Revit, ArchiCAD, Rhino, or SketchUp. Revit software has built-in capabilities for performing UOBs 2.1.2 to 2.1.6. A knowledgeable Architect can utilise these tools to make informed decisions regarding the building massing. Furthermore, Sefaira software's plug-ins can be utilised with Revit or SketchUp. If a Sustainability Engineer is required, the analysis can take place in IES-VE software, which also provides more accuracy. The optimisation of the building's orientation (UOB 2.1.4) is achieved by rotating the building axis from 0 to 90 degrees and simulating the heating and cooling loads that are achieved for each orientation. This technique is part of the Sensitivity Analysis method described in Ternoey et al. (1985). The final optimised BIM Arch (LOD100) is issued in the CDE (e.g. 4Projects, BIW by Conject, aconex, BOX). The preliminary outline design needs to be approved by the Client before the decisions are frozen. If the Client does not approve the proposal, the process iterates to UOB 2.1.1.

UOB	***WHY***	***WHO***	***WHAT***	***HOW***
Optimise fabric and layout (UOB 2.2)	The targets at this stage are to optimise the fabric performance by utilising passive design strategies (e.g. daylight autonomy, solar gains, natural ventilation, thermal mass effects and night cooling). This would result in minimising energy requirements and promoting human comfort and health inside the building.	The Architect, who is responsible for authoring the BIM Arch (LOD200), should have the ability to manipulate a 3D model, along with the experience in construction methods and means. The Sustainability Engineer role must have the ability to navigate, manipulate and review a 3D BIM. Furthermore, they need to have a good knowledge of environmental design principles, material properties and specifications, and building regulations regarding the sustainability measures' implementation. The Structural Engineer sizes the structural elements and assesses their performance.	Table 7.10 contains the information requirements to perform the tasks of UOB 2.2. The first row shows the information that should be contained at the BIM Arch LOD200 submitted to the Sustainability Engineer for analysis. The outputs of the performance analyses (rows 2-6), should be interpreted and explained in a PDF report or PowerPoint presentation that contain recommendations and advice for the design team. The outputs of the structural analysis are a BIM Struct LOD200, and a report.	The Architect should utilise a BIM authoring tool such as Revit, ArchiCAD, or Microstation to develop the LOD200 BIM containing the fabric information. The model should be uploaded in the CDE in an IFC or gbXML format. Each space/room should be designed as a single thermal zone that contains the occupancy requirements and the properties of its elements. If there is an in-house Sustainability specialist, tools such as Sefaira and EcoDesigner offer reliable results, although not NCM accredited. For accurate results, which comply with the building regulations, an accredited software package such as IES-VE, Hevacomp, TAS, and DesignBuilder must be utilised. The Sustainability Engineer should upload the performance analysis report in the CDE. The Structural Engineer utilises Revit for early structural design and analysis. When the design solution is approved by the Client, Architect, Structural, and Sustainability Engineer, the BIM Arch LOD200 is marked as optimised and the design can progress to the next stage.

UOB	WHY	WHO	WHAT	HOW
Configure mechanical services (UOB 2.3)	The sustainability intent at this stage is the selection of efficient services that require the minimal amount of energy, while delivering the heating and cooling loads required. Furthermore, the use of clean energy sources from renewables (e.g. sun, wind) is preferred to conventional sources (e.g. petrol). The sizing of the plant rooms, ducts, and their routes are important considerations at this stage. Compliance with Part L of the UK Building Regulations is a mandatory requirement.	The MEP Engineer is authoring the services model, identifying the size and location of the plant rooms and the duct sizes and routes within the building. The ability to manipulate, review and author 3D BIMs is needed. The Sustainability Engineer should be able to review the 3D BIM, author a 3D BPA model in dynamic simulation software (e.g. IES-VE, Hevacomp, TAS), perform the analysis, and interpret the results. The BIM Coordinator should be able to manipulate 3D models and identify the constructability of the design. Good knowledge of building systems is required to identify the clashes and resolve potential issues.	Table 7.10 shows the information requirements for UOB 2.3 tasks. The outputs of UOB 2.2 (Table 7.10) are required for performing UOB 2.3.1 to 2.3.4. To determine the energy sources (UOB 2.3.1), site information analysis is required regarding their availability on, or close, to the site. To develop the artificial lighting strategy (UOB 2.3.2), the daylight autonomy needs to be determined first (UOB 2.2.5). The target illuminance levels, lighting zones of artificial lighting, their controls, and the selection of lamps are the outcomes of UOB 2.3.2. (CIBSE Guide L and CIBSE Guide SLL (2012b)). The sizing of HVAC systems responds to the heating and cooling loads, identified in UOB 2.2.7 (CIBSE Guide B (2012a), ANSI/ASHRAE Standard 62-2001). The outputs of UOB 2.3.5 are identifying the location of the plant room(s), estimating the sizing and routes of ductwork. The selection of efficient HVAC equipment is the main consideration of UOB 2.3.1 to 2.3.5 (CIBSE Guide F). The thermal loads/heat gains as well as the energy consumption of IT, small equipment, and lighting should be assessed explicitly in order to make realistic estimations. Water systems strategies (e.g. water harvesting, water recycling) need to be considered at this stage (UOB 2.3.4). It is recommended not to oversize the plant based on peak heating and cooling loads. Localised solutions may be implemented instead for specific times, when required. The Arch, Struct, and MEP LOD200 BIMs are required to perform the coordination exercise (UOB 2.3.12). The output of UOB 2.3.12 is a coordinated LOD200 BIM with information attached.	The MEP Engineer utilises Revit, AECOSim, CAD Duct, or other 3D authoring tools to create the LOD200 BIM (UOB 2.3.1-2.3.5). The functions of UOB 2.3.6-2.3.11 may occur concurrently in Revit utilising the cloud-based facility for early design calculations. For more accuracy, UOB 2.3.6 to 2.3.11 can be assessed in IES-VE software. The MEP LOD200 BIM, along with the analysis report are uploaded in the CDE. The coordination of the Arch, Struct, and MEP BIMs requires the use of coordination software tools such as Navisworks and Solibri. The former is considered simpler in use, while the latter offers more capabilities (e.g. creation of rules).

UOB	WHY	WHO	WHAT	HOW
Optimise and refine concept (UOB 2.4)	The optimisation of concept design occurs by assessing the trade-offs of design solutions while assessing the implications on environmental performance and cost.	The Client, Architect, MEP Engineer, Structural Engineer, Sustainability Engineer, and Cost Consultant/Contractor work collectively in a holistic iterative process.	The information requirements of Table 7.10 are manipulated to reach LOD200. The outcome of the UOB 2.4 is a Federated Model consisting of component models (Arch, Struct, MEP), drawings derived from the models, and data sources. A cost estimation report (Table 7.10), and a BREEAM design stage pre-assessment (J17) are also required.	An iterative process of developing, analysing/assessing, and reviewing the individual proposals until a consensus is reached between the project team members. The working methods for UOB 2.4.1 to 2.4.5 resemble the ones of UOB 2.1 to 2.3. For assessing UOB 2.4.6 - 2.4.12, dynamic simulation BPA is required for accurate results before freezing the design solutions. For that purpose, NCM accredited simulation software (e.g. IES-VE, TAS, Hevacomp, and DesignBuilder) should be utilised before committing to decisions. Revit performs early cost analysis but dynamic cost modelling in Excel or specialised software is highly recommended (e.g. TurboBid Estimating, HCSS HeavyBid, Viewpoint MEP Estimating, B2W Estimate - Estimating and Bidding, ProContractor™ by Viewpoint) (UOB 2.4.13). The documents for BREEAM pre-assessment can be uploaded in Tracker Plus or IES TaP.

Table 7.12 Sustainability benchmarks for decision points J4, J8, J10, and J17 (office building example)

Decision points	Sustainability criteria	Sustainability benchmarks		
		Minimum requirement	Best practice	Innovative
Junction J4	4.1. Overshadowing	45 degree rule (Rights of Light Act 1959, 1959 Chapter 56 7 and 8 Eliz 2)	Design in accordance to the sun path diagram for specific times and dates of the year.	N/A
	4.2. Building height	Local planning authority	Minimal disruption to neighbouring buildings.	N/A
Junction J8	8.1. Embodied carbon of materials	Not assessed, but preference in locally sourced materials is stated.	Minimise materials' mass. Replacement of cement with materials with less embodied carbon. Specification of locally sourced materials.	Detailed lifecycle material selection. Low carbon materials almost entirely. Carbon profile of building created.
	8.2. Toxicity of materials	Avoidance of VOCs (Volatile Organic Compounds) materials and all ozone-depleting materials (BRE Green Guide).	Use of LSF (Low Smoke and Fume) instead of PVC (Poly Vinyl Chloride) cabling. No petrochemical materials used for insulation. Avoid all "C" rated materials (BRE Green Guide).	VOC-free paints and timber use. Use of natural materials. 80% of materials rated "A" and "A+" (BRE Green Guide).
	8.3. Recycled materials	15% recycled material	30% recycled material	Over 45% recycled material
	8.4. Glazing and shading	Orient and size windows for capturing useful daylight only. Provide external shading.	Automatic adjustable shading. Use of planting for shading.	Additionally to previous, insulated shutters/blinds with reflective properties.
	8.5. Daylighting	Narrow plan floor-plate or roof-lights to provide daylight. 80% floor area > 2% daylight factor and uniformity 0.4. Views to sky shown (CIBSE Lighting guide 10 (2012b), BS8206 Part 2 (2008)).	Additionally to previous, 80% floor area over 3% daylight factor (BREEAM UK Technical Manual, issue 2.0, 2014).	Additionally to previous, 80% floor area over 5% daylight factor. Provision for glare (use of light shelves). Building form led by daylight design.
	8.6. Insulation (U-Values, W/m^2K)	2013 Part L regulation	2016 Part L regulation	2019 Part L regulation, zero carbon
	8.6.1. Wall	0.2	0.15	0.1
	8.6.2. Window	1.4	1.1	0.8
	8.6.3. Roof	0.15	0.12	0.1
	8.6.4. Ground floor	0.15	0.12	0.1
	8.7. Airtightness (at 50Pa)	$3.5m^3/h/m^2$ (BCO Guide)	$2.0m^3/h/m^2$	$1.0m^3/h/m^2$
	8.8. Ventilation and cooling	Use of free cooling where possible. Natural ventilation or mixed mode with heat recovery. Thermal mass on roof (ANSI/ASHRAE Standard 62-2001).	Free cooling maximised. Natural ventilation and use of Ground Source heat Pumps (GSHP) or mechanical ventilation with heat recovery.	N/A
	8.9. Overheating and climate change	BCO (British Council of Offices) targets and test (UK Climate Impacts Programme) UKCIP2020 (Supporting society in adapting to climate change). ISO7730 dress code.	Maximise adaptive comfort. Test UKCIP 2050 (Supporting society in adapting to climate change). CIBSE (2013) TM52: The Limits of Thermal Comfort: Avoiding Overheating in European Buildings.	Test UKCIP 2080 (Supporting society in adapting to climate change).
	8.10 Acoustic performance	Internal indoor ambient noise levels (Section 7 of BS8233:1999) (2014).	Achieve the requirements relating to sound absorption and reverberation times (Section 7 of BS8233:1999).	N/A

Decision points	Sustainability criteria	Sustainability benchmarks		
		Minimum requirement	Best practice	Innovative
Junction J10	10.1. Energy consumption	2013 Part L regulation	2016 Part L regulation	2019 Part L regulation, zero carbon
	10.1.1. Heating and hot water	46kWh/m²/yr	30kWh/m²/yr	15kWh/m²/yr
	10.1.2. Electrical load	15kWh/m²/yr	13kWh/m²/yr	12kWh/m²/yr
	10.1.3. IT and small power	41kWh/m²/yr	33kWh/m²/yr	26kWh/m²/yr
	10.2. Carbon/CO_2 emissions	21kg CO_2/m²/yr	8kg CO_2/m²/yr	0kg CO_2/m²/yr
	10.3. Display Energy Certificate (DEC)	D or C rating	B rating	A or A+ rating
	10.2. Energy consumption	2013 Part L regulation	2016 Part L regulation	2019 Part L regulation, zero carbon
	10.3. Energy source	20% renewables and compliance with local planning authority	More than 20% on site renewables	50-100% on-site energy generation or agreed offsite
	10.4. Artificial lighting	300 lux background lighting plus task lighting (SLL Lighting Guide LG7 (2012)).	150-200 lux background lighting plus task lighting. Daylight dimming and presence detection utilised.	Additionally to previous, plus innovative technologies such as LEDs.
	10.5. Water consumption	4.5m³/person/yr	1.5m³/person/yr	less than 1.5m³/person/yr
Junction 17	17.1. Controls and metering	Seasonal commissioning. Production of DEC (Display Energy Certificate).	Detailed monitor over first year	Continual monitoring and formal external review. Results published to industry. Energy use reward/penalty system.
	17.2. IT strategy	Users encouraged switching off PCs overnight.	Kill switch for non-essential peripherals. Utilisation of laptops throughout.	Low power terminals with centralised computing. Running cloud-based and virtualisation software.
	17.3. Capital cost	Ensure reduction of CapEx is well supported.	Building Cost Information Service of RICS (BCIS) Standard Form of Capital Cost Analysis (2012), ISO 15686-5.	N/A
	17.4. Lifecycle cost	Design team encouraged to have a clear scope and structure for presenting the costs.	Standardized Method of Life Cycle Costing (Royal Institute of Chartered Surveyors (RICS, 2016))	N/A
	17.5. Occupancy & user involvement	Use industry standards. Client briefing. FM team trained at building handover.	Additionally to previous, stakeholder consultation. All users involved in understanding building function and controls. Non-technical guide produced.	Additionally to previous, design strategy is tested with stakeholders. Feedback results are fed into industry standards. Soft Landings framework followed.
	17.6. BREEAM rating	Pass (≥30) or Good (≥45)	Very Good (≥55) or Excellent (≥70)	Outstanding (≥85)
	17. 7 Energy Performance Certificate (EPC) score	Over 76 (D-G rating)	B (26-50) or C (51-75)	A (0-25) or A+ (Net zero CO_2 emissions)
	17.8 Robustness to climate change	N/A	Carry out a systematic (structural and fabric resilience specific) risk assessment to identify and evaluate the impact on the building over its projected lifecycle from expected extreme weather conditions arising from climate change and, where feasible, mitigate against these impacts (for 60 years).	Perform adaptation to climate change calculations for 100 years.

7.6. Summary

This Chapter has presented the validation of the research outputs through both academic and industrial evaluations. The feedback received during these exercises has revealed that the outcomes of this research provide a timely solution to the problem of BIM-enabled collaboration for SBD. Therefore, it has been demonstrated that the main principles that this process should follow are: (i) clear definition of sustainability objectives before design implementation and delivery, (ii) frequent feasibility checks for sustainability goals/benchmarks, (iii) iterative process of building design and sustainability assessment, (iv) concurrent parallel tasks, and (v) clear rules with an amount of customisation for bespoke projects. Moreover, it has been indicated that the concept of GBB could facilitate automation of workflow management for SBD, which can assist in achieving environmental design objectives in the most economical way possible in terms of time, cost, and effort. The second part of the Chapter has synthesised the findings of the research and presented the refined IDEF process model, revised after the validation exercises. Due to the fact that an extensive review process has taken place, it has been consolidated that the components of BIM-enabled SBD can be defined in an explicit and detailed way. Furthermore, the relationships between them, which include sequence of events, parallel activities, and decision points can be generalised for a wide range of non-domestic projects, both in the UK and the rest of Europe. The next, and final Chapter, discusses the main research findings and contributions to knowledge, along with limitations and opportunities for further research.

Chapter 8

Conclusion

8.1. Introduction

This Chapter reviews this research study and provides a synopsis of the investigation by drawing together the main conclusions from each of the previous Chapters of the thesis. The main goal of this study was to investigate, model, and facilitate the BIM-enabled SBD process. Hence, the focus was on the improvement of multidisciplinary collaborative SBD management by providing a systematic account for its planning and delivery. The following Sections demonstrate how the research objectives have been achieved, and summarise the lessons learnt during this research along with the implications of the project's outcomes for SBD implementation. Moreover, the Chapter discusses the limitations of this study and suggests recommendations for future work.

8.2. Discussion of main findings and reflections

This Section describes the major findings and main conclusions drawn during this research investigation. These include the definition of SBD and the identification of its problems, as well as the development of a theoretical framework and model for its implementation utilising the existing technological enablers such as BIM, BPA, and ICT. For this purpose, the following sub-Sections are aligned with the research objectives (1-6), presented in Chapter 1 (Section 1.3).

8.2.1. Definition of sustainability goals and discussion of existing models of SBD

Objective 1: *"To explore the definition of sustainability and the existing models for the design process in order to identify the main problems in SBD management."*

A comprehensive literature review survey was performed in order to identify the design goals of SBD, and the findings of this investigation are presented in Chapter 2.

Among the three dimensions of SD (i.e. Environmental, Social, and Economic), the environmental design goals are the most prominent for assessing building performance. The main aspects that environmental design considers are human comfort and health, and environmental impact including the use of natural resources. To address these considerations, several rating systems (e.g. BREEAM, LEED) have been developed by organisations worldwide in order to provide a holistic assessment of SBD outcomes. These frameworks are commonly utilised as checklists for the design process. However, this practice is not appropriate since they provide little guidance regarding the process of building design (Cole, 2005). Thus, it has been inferred that a holistic SBD process guidance system is currently missing for multidisciplinary collaboration.

Designers implement a combination of passive and active design strategies in order to achieve sustainability goals based on the micro and macro climatic conditions at the building site (Brown and DeKay, 2000; Zeiher, 1996; Allen, 1995). Nevertheless, the process for their implementation has not been sufficiently defined for multidisciplinary collaboration. Due to the fragmented way of working, the existing building design processes do not effectively permit the integration of sustainability considerations from the early stages, hence compromising the achievement of sustainability objectives. On the other hand, CE principles have been successfully implemented, in manufacturing, for mapping the design process so as to make it explicit. Arguably, the mapping of the building design process presents the biggest challenge since its nature is fundamentally different from the manufacturing process (Hassan, 1996). Therefore, prescriptive approaches to SBD management are not considered suitable for its implementation. For this reason, a mixture of descriptive and prescriptive elements comprise the model developed in this study (discussed in Chapter 2, Section 2.3.3).

8.2.2. Opportunities for improvement of SBD management utilising technological enablers

Objective 2: "*To examine the use of the state of the art technological advancements in BIM, BPA, and ICT so as to identify gaps in the existing knowledge for SBD*."

An extensive literature review (see Chapter 3) along with in-depth interviews with industry experts (see Chapter 5) have served to determine the current implementation methods of collaborative SBD. Subsequently, it is established that the existing technological enablers such as BIM, BPA, and ICT have proven benefits for managing the design process (DTI, 2007b). For sustainability, though, their integration remains low due to the lack of a comprehensive process for BIM-enabled SBD implementation and delivery. In order to reach their potential, re-thinking of the existing collaboration processes is required (Garber, 2009). Therefore, to make a step change towards SD, assisted by the new technological improvements (i.e. software, hardware, and networks), there is a need to specify the components and processes of BPA within BIM collaboration. The challenge that this incorporation faces is the coordination of all available elements, which are necessary to achieve optimum results (Ruikar et al., 2006). To do this, critical SBD decisions should be considered timely in order to assess trade-offs between design aspects that are delegated to disciplines with varying specialisations.

It has been found that recent research studies have mainly focused on the technology aspects of BIM. These have resulted in producing: (i) conceptual frameworks to test interoperability and capabilities of common simulation tools (Azhar, 2011; Bazjanac, 2008; Che et al., 2010); (ii) frameworks integrating international assessment rating systems (Biswas and Wang, 2008; Ghosh et al., 2011; Wong and Fan, 2013); and (iii) automated decision-making tools (Brahme et al., 2001; Schlueter and Thesseling, 2009; Welle et al., 2011; Geyer, 2012; Gerber and Lin, 2014). Nevertheless, it has been proven that managerial issues in construction information systems are more influential than technology issues (Jung and Kang, 2007). However, organisational aspects of BIM-enabled SBD have not been addressed sufficiently in the literature (Mills and Glass, 2009; Opoku and Ahmed, 2013). To date, there is still no comprehensive and structured process to assist professionals for the planning and delivery of SBD, from the early stages, so as to harness the talents of all building professionals' disciplines, and achieve optimum results.

8.2.3. Identification and definition of BIM-enabled SBD components

Objective 3: *"To develop and verify a theoretical framework for BIM-enabled SBD implementation that defines the components of the process."*

An extensive literature review along with in-depth interviews with industry experts, utilising content analysis (Elo and Kyngäs, 2008) and thematic analysis (Braun and Clarke, 2006) methods, have served to identify and define the elements that constitute the BIM-enabled SBD process (see Chapter 5). Moreover, the framework has been validated through academic and industrial reviews (see Chapter 7).

During this study, the importance of incorporating all design disciplines from the early stages of SBD has been affirmed. This notion has been widely acknowledged and documented in the literature (Bouchlaghem et al., 2005; Mills and Glass, 2009), while it is also stressed that early decisions are crucial in order to achieve sustainability in the resulting design outcome (Schlueter and Thesseling, 2009). It has been found that ad hoc processes that are currently followed, for organising SBD, have failed to deliver the correct sustainability information that each role needs to perform their duties, during SBD implementation, resulting in increasing uncertainty to achieve sustainability goals. In order to enable (BIM) technologies to reach their full potential, the roles within the design team need to be clarified, along with their tasks and deliverables, so as to become meaningful and useful for multidisciplinary collaboration. For this reason, this research has focused on defining the roles, responsibilities, and competencies, which are necessary for the implementation of SBD, along with their contributions during the early design stages. As a result, Schedules of Services for SBD have been developed for the three earlier stages of the RIBA Plan of Work 2013 (see Tables 5.2, 5.3, and 5.4): stage 0 (Strategic Definition), stage 1 (Preparation and Brief), and stage 2 (Concept Design).

In addition, the findings from the interviews have revealed three pillars for SBD aspirations: (i) occupant comfort and health, (ii) environmental impact, and (iii) client satisfaction and approval. It has been argued that the definition of sustainability needs to be re-framed as the level of detail of design increases (Becker, 2008). Therefore, this research has aligned sustainability considerations to the RIBA Plan of

Work 2013 stages 0, 1, and 2 (see Figure 8.1). Sustainability considerations need to be expressed qualitatively at stage 0, then, quantified (e.g. metrics, benchmarks) at stage 1, and finally, tested and defined explicitly at stage 2. Feasibility of the sustainability criteria is the basis for optimising the design, by performing iterations at Concept Design (stage 2). Thus, it is important for design practitioners to ask the appropriate questions at each stage of the SBD process.

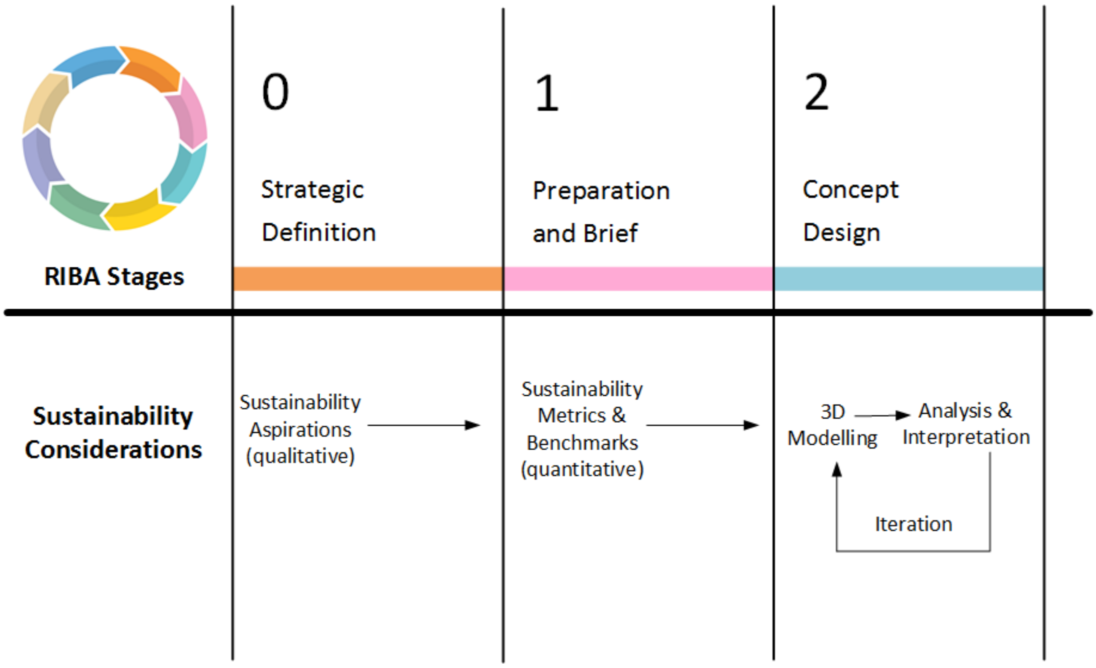


Figure 8.1 Sustainability definition aligned with the RIBA Plan of Work 2013

This research has also discussed the opportunities, challenges, and limitations for the implementation of BIM-enabled SBD tasks, utilising the existing technological enablers. This includes, but is not limited to, the selection of BIM and BPA tools along with their interoperability issues. Furthermore, it has been found that the criteria for selecting BPA software are the: (i) speed of analysis (e.g. Revit plug-ins, Sefaira, PHPP), (ii) accuracy of analysis (e.g. PHPP, IES-VE), (iii) compliance with NCM accreditation (e.g. IES-VE, Hevacomp, EcoDesigner), (iv) breadth of capabilities (e.g. Sefaira, IES-VE), (v) interoperability (plug-in or open standards), and (vi) prior experience with the tools. The processing power of computers is another important consideration for the use of detailed dynamic performance modelling. The findings suggest that the geometric information and properties of BIM models, if designed properly, can be seamlessly translated to be recognised by BPA software tools. However, as it was reported by the participants, the opposite process was not possible at the time. This fact is a technological limitation that has hindered integration of sustainability information directly into BIM.

It has been inferred that despite the capabilities of BIM software, there has been consensus among the designers that the design process is heavily driven by 2D drawings. Despite working in certified Level 2 BIM maturity projects, the interviewees have claimed that, for SBD, it has not affected collaboration with other disciplines in a way that is anticipated in theory. The participants argued that for the process to be functioning successfully, the architectural model should be built having BPA in mind. A transparent process can assist practitioners appreciate what the other disciplines need in order to perform their duties. Nevertheless, duplicate work has been hindering the SBD process; the interviewees reported having to reconstruct the BPA model in order to perform sustainability analysis. However, timely performance assessment is critical for the Architects to be able to make informed design decisions and progress into more design detail. By reconstructing the BPA model from scratch, the Sustainability Engineers have been unable to provide feedback on the sustainability performance of the building timely, increasing the possibility of failing to achieve sustainability targets.

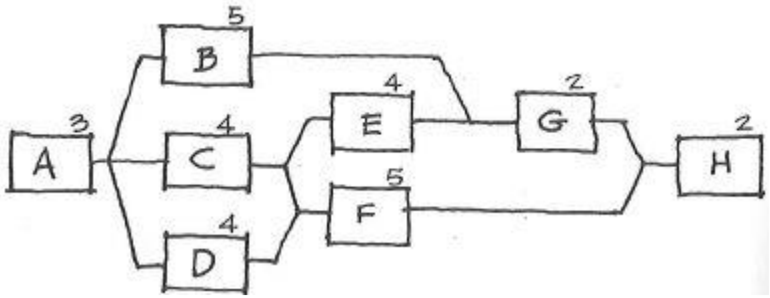
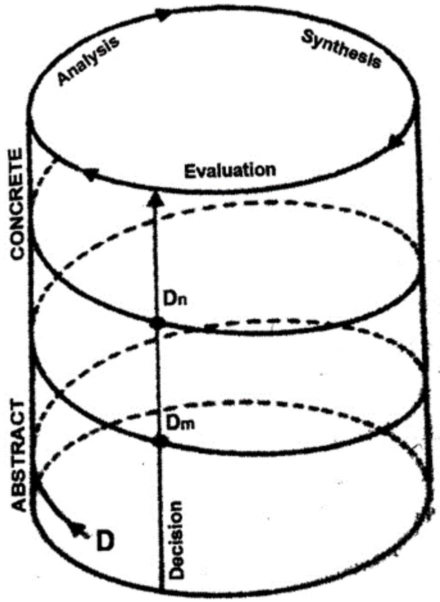
8.2.4. Rules-based coordination of SBD tasks and deliverables

Objective 4: *"To create, evaluate, and refine a structured holistic process model for BIM-enabled SBD collaboration, which establishes the relationships between components."*

The IDEF process model, for BIM-enabled SBD, was developed through a series of inductive and deductive steps (abductive approach), as described in Chapter 4 (Section 4.7). In-depth semi-structured interviews, utilising the Critical Decision Method (CDM) (Klein et al., 1989), have assisted in identifying the workflow patterns that took place during collaborative design of sustainable buildings, and reflect on their outcomes based on lessons learnt (successes and failures) of the best practices. The complete IDEF process model (before validation) can be found in Appendix D. Finally, the model was evaluated and refined by performing validation exercises with industry practitioners (see Chapter 7, Section 7.4).

It has been supported that traditional working processes cannot be employed to achieve complex high-performing buildings, and that a CE design process approach to SBD is essential. During the traditional building design process, each stakeholder passes fixed information to the next one, which results in compromised design outcomes. What the CE approach suggests, for SBD, is that design solutions are developed, assessed, and revised collaboratively, as design progresses. Therefore, a single linear prescribed process is not viable, for SBD, because the complexity, amount of specialisation and individual project needs do not permit the process to be defined without iterations. The proposed SBD process, developed in this research project, combines the sequential principles found in organisational design theory (task-oriented network) (Laseau, 2001) with the spiral metaphor (from abstract to concrete design concept) of the design process (Goldschmidt, 2014; Watts, 1966) (see Table 8.1). Thus, this research aimed to improve BIM maturity level for SBD, assisting in the transition from "*ad hoc*" to "*defined*", and then, to "*managed*", as described by Succar et al. (2012). The process offers a true reflection of what needs to happen during SBD implementation so that every member of the design team can see value-adding steps. As a result, by following this process, stakeholder communication and information flow can be improved.

Table 8.1 Task-oriented network vs spiral metaphor of the design process

Task-oriented network (Laseau, 2001)	**Spiral model of design process** (Watts, 1966)
	

The importance of decision points has been stressed in PAS 1192-2:2013 (BSI, 2013b) as a critical aspect of the BIM collaborative process. For this reason, this research has identified the critical decision points, for SBD, and has aligned those with the appropriate sustainability considerations and criteria. The SBD decision points comprise two types of gates; hard-gates when the design freezes until the review is conducted, and soft-gates that allow the project to proceed in parallel, thus enabling a CE approach to SBD. It is suggested that the hard-gates serve the purpose of committing to decisions collectively. Additionally, soft-gates are identified throughout the process so that the decision making points occur in parallel. Instead of design participants working in isolated silos, between the hard-gates (start and end of Concept Design), the soft-gates identified during the Work In Progress (WIP) phase (BSI, 2013b) can facilitate communication by triggering design tasks so as to clarify the process for SBD practitioners and reduce uncertainty.

It has been derived that the contributions of a variety of expertise's roles, during SBD development, result in a front-loaded process, as described by the MacLeamy curve (CURT, 2004). Furthermore, the findings show that the process can be mapped in a more detailed manner than the RIBA Plan of Work (2013). The collaborative patterns, at Concept Design stage, are found to be repeatable for a variety of different non-domestic building types such as education, healthcare, and offices. Thus, repeatable tasks and similar workflow patterns, along with roles and responsibilities have been identified. This fact has enabled the development of a systematic approach to SBD, based on CE principles (Love and Gunasekaran, 1997; Gunasekaran and Love, 1998). This approach would allow lessons learnt to be incorporated for the design of future buildings.

8.2.5. Formal and informal communication in a centralised system

Objective 5: *"To analyse and visualise a workflow management system that facilitates the structured process developed."*

The IDEF process model, developed in this research, can be utilised within a CDE to facilitate the implementation of a collaborative SBD process for Concept Design. So as to analyse the delivery of BIM-enabled SBD, Green BIM Box (GBB) conceptual workflow management prototype tool has been developed as a recommendation. GBB formalises SBD goals, roles, responsibilities, methods, and deliverables coordinating them into a common process holistically. Chapter 6, Section 6.4, presents the development of GBB system's architecture for SBD process automation. Its structure and schematics are described through Use Case Scenarios (Carroll, 1995) utilising Sequence Diagrams and the UML notation (OMG, 2011). It is suggested that the IDEF model can act as the Service layer in a three-layer system design (Buschmann et al., 1996). As such, its role would be to coordinate the top (Presentation) and bottom (Data and Knowledge Access) layers by containing the logical decisions and the commands of the application. Screenshots of the Presentation layer (GBB mock-up), and an illustration of the Data and Knowledge Access layer (Entity Relationship Diagram, ERD) (Chen, 1976) can be found in Appendix D. Furthermore, the practitioners' attitudes towards the GBB concept are discussed in Chapter 7.

GBB has been developed to address the issue of informal and formal communication that emerged from the case studies' narratives. Drawings, contractor's programmes, and other information represent formal communication, and day-to-day communication represents informal organisation. Inconsistencies between the two exist due to the lack of project team alignment for SBD. The interviewees described the role of the Sustainability Engineer as prominent, in the early design stages. However, their collaboration cannot be secured, with the current procurement methods, since in most cases their communication with the Architect occurs informally and is not recorded in the formal systems. Therefore, their contribution in the SBD process is severely underestimated. In order to move from spider-web communication architecture to a hub-centric one, within a CDE, the existing communication patterns need to be understood to inform the centralised system. The findings show that the SBD process is iterative and it is about assessing, revising, and re-assessing sustainability as design progresses. This principle aligns with the cyclic design paradigm proposed by Asimow (1962). Based on the incidents' narratives, this research has determined the design-assessment loops that occur between Concept Design's soft-gates, as shown in Figure 8.2.

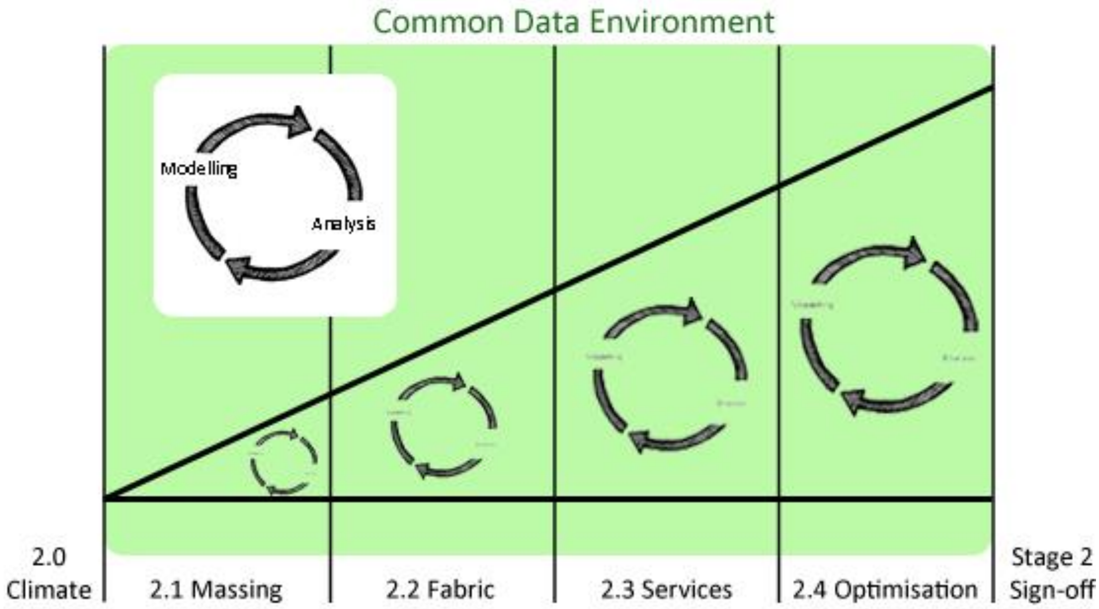


Figure 8.2 Soft-gates and assessment loops for SBD during Concept Design (RIBA stage 2) development

8.2.6. Evaluation of research outcomes and implications for SBD practice

Objective 6: *"To assess the benefits of the research outcomes for improving the management of the SBD process and make recommendations for further research."*

The validity and reliability of the research outcomes have been established through eight cycles of academic and industrial reviews that have led to the refinement of the process model and framework for BIM-enabled collaborative SBD (see Chapter 7). The IDEF process model has been iteratively validated and refined through a presentation in an academic conference (CECAR6), publication in two academic journals (IJESM and AEDM), and seven in-depth interviews with industry practitioners, experts in SBD. Furthermore, the conceptual workflow management system (GBB) was presented in two academic workshops with eight participants, and was discussed during interviews with seven industry experts.

There was consensus amongst participants regarding the usefulness and adequacy of the IDEF process model for the implementation of collaborative SBD. The participants considered the research output to be very well-structured, clear, relevant, comprehensive, and easy to understand and navigate. Furthermore, they have acknowledged its value as a guideline for considering the most critical aspects of sustainability at Concept Design stage, and for communicating them among the design team for better alignment. Overall, the feedback was enthusiastic with the interviewees emphasising on the appropriateness of the sustainability considerations, terminology, and sequencing of events. Additionally, minor alterations to the process model were recommended for its refinement. Moreover, the participants supported the argument that the research outcomes (process model and GBB) fill an existing gap in industry practice and could potentially offer better control over the SBD process. Finally, the participants believed that automation of workflow management, for SBD, could assist in achieving sustainability objectives in the most economical way possible in terms of time, cost, and effort. Therefore, the results of this study indicate the following as the main principles for SBD implementation: (i) clear definition of sustainability objectives before design delivery, (ii) frequent feasibility checks for sustainability goals and benchmarks, (iii) iterative process of building design and sustainability assessment, (iv) concurrent parallel tasks, and (v) clear rules with an amount of customisation for bespoke projects.

8.3. Contribution to knowledge and potential impact

This research has argued that the most significant challenge to delivering a successful sustainable building is communication and coordination across a multidisciplinary team (Mills and Glass, 2009; Robichaud and Anantatmula, 2010). A comprehensive literature review survey, combined with empirical evidence from 14 case studies, has revealed that the design process still suffers from lack of collaboration between design teams of different organisations. Therefore, it has been confirmed that the most common problem to achieve a sustainable outcome is the absence of appropriate information to make critical decisions (DTI, 2007b). BIM is considered a way to address fragmentation in the AEC/O industry (Cabinet Office, 2011) but, to date, there is little understanding of how sustainability considerations could be incorporated within BIM collaborative processes.

Several research studies have resulted in producing conceptual frameworks to test interoperability and capabilities of common simulation tools (Azhar et al., 2011; Barnes and Castro-Lacouture, 2009; Bazjanac, 2008; Che et al., 2010; Hamza and Horne, 2007; Hetherington et al., 2011; Lee et al., 2007; Magent et al., 2010; Maile et al., 2007). Moreover, some BIM related frameworks have been based on the international assessment rating systems (Biswas and Wang, 2008; Biswas et al., 2009; Ghosh et al., 2011; Lützkendorf and Lorenz, 2006; Nofera and Korkmaz, 2010; Sinou and Kyvelou, 2006; Wong and Fan, 2013), and regulations (Kasim, 2015; Cardiff University, 2007). Others have created tools that are integrated into BIM to automate performance based decision-making (Brahme et al., 2001; Feng et al., 2012; Huber et al., 2011; Schlueter and Thesseling, 2009; Welle et al., 2011). On the other hand, organisational approaches for collaborative SBD (Mendler and Odell, 2000; Laseau, 2001) have resulted in generic descriptive models such as the RIBA Plan of Work 2013 (RIBA, 2013a; RIBA, 2013b) that considers sustainability aspects in a checklist without integrating them into the design process along with the core objectives. Other attempts to integrate sustainability considerations into the building design process lack the element of sequencing of activities (Cinquemani and Prior, 2010; Bordens and Abbott, 2002; Reigeluth, 1999), and reasoning of decisions (Potts and Bruns, 1988; Lewis and Mistree, 1998). Therefore, this study has argued that a detailed structured BIM-enabled collaborative design process can improve multidisciplinary communication, and thus, assist in achieving sustainability objectives more efficiently in terms of time, cost, and effort.

This research has adopted an abductive reasoning approach (Kolko, 2010) during an iterative theory building process (Drongelen, 2001) that consisted of a series of inductive and deductive steps (Dubois and Gadde, 2002; Levin-Rozalis, 2004; Reichertz, 2004; Svennevig, 2001). Empirical evidence (qualitative and quantitative), which were collected during 4 stages of data collection (32 in-depth semi-structured interviews), have been triangulated with sustainability, design management, and organisational theories. Content (Elo and Kyngäs, 2008) and thematic analysis (Braun and Clarke, 2006) have been implemented to develop a framework of components that constitute BIM-enabled SBD (i.e. roles, tasks, deliverables, and decision points).

Furthermore, the CDM (Klein et al., 1989) has been utilised to identify collaborative workflow patterns of the best practices. IDEF0 (KBSI, 1993) and IDEF3 (Mayer et al., 1995) structured diagramming techniques have been used to create a formal CE model of the BIM-enabled SBD process, which holistically combines "*top-down*" organisational with "*bottom-up*" performance-based perspectives into a single view. The framework and model clearly define the roles, responsibilities, and competences that are essential to achieve SBD. Moreover, the research outcomes provide an appropriate scoping of BIM Uses, BIM Deliverables, and sustainability considerations for the early design stages, integrated within the RIBA Plan of Work 2013 (stages 0-2). Thus, this systemic approach has balanced sequential descriptive principles (task-oriented network) with cognitive elements (decisions from abstract to concrete design concept). What is more, the UML notation (OMG, 2011) has served to demonstrate (through Use Case Scenarios) how the developed process model can be used to facilitate synchronous and asynchronous communication within a centralised system (CDE). GBB conceptual workflow management prototype tool has been developed based on the above analysis. Thus, this research has strived to improve BIM maturity (for SBD) from "*ad hoc*", to "*defined*", and then, to "*managed*" so as to align with the UK Government's Level 2 BIM mandate (Cabinet Office, 2011). Finally, the trustworthiness and reliability of the research outcomes have been validated through academic (2 conference papers, 2 journal articles, 2 workshops) and industrial (7 interviews with experts) reviews. A number of quality control exercises have also been considered during this research project to ensure the validity (construct, internal, external) and reliability of the research outcomes. Those have included a thorough literature review, theoretical sufficiency, low inference descriptions, theoretical generalisation, member checking, peer review, extended field work, transparency, self-disclosure, and procedural ethics.

As a result, the research outcomes aim to promote sustainability so as to enhance human comfort and health within buildings, while also reducing the use of natural resources and environmental pollution. It is believed that this can be achieved through the efficient use of technological enablers such as BIM, BPA, and ICT. Therefore, it is argued that a transparent, holistic, and comprehensive process can assist in improving coordination across multidisciplinary distributed teams so as to provide quality assurance for SBD. The research outcomes can facilitate the development of a Digital Plan of Work (DPoW) for BIM-enabled SBD, which could potentially standardise the creation of EIR (Employers Information Requirements) and BEP (BIM Execution Plan) for sustainability. Moreover, GBB can be used to manage the DPoW agreed processes and deliverables. Nevertheless, while the developed concept aligns with the UK standards for information management (BS 1192:2007, PAS 1192-2:2013), it also suggests a CE approach during WIP. This approach adds a new dimension to the above standards by encouraging communication, instead of isolation, during WIP. It is supported that a common definition for multidisciplinary SBD can promote better collaboration by harnessing the intellectual inputs of stakeholders with varying areas of expertise. Therefore, the developed Scope of Services (see Section 5.3.1) can assist in creating more detailed contractual agreements in which the contributions of all stakeholders are appreciated and compensated accordingly. Furthermore, this detailed approach can assist in the development of more realistic front-loaded project programmes that take into account the existing UK Building Regulations (e.g. Part L) and sustainability certifications (e.g. BREEAM, LEED, Passivhaus).

8.4. Limitations of the study

This study has several limitations that need to be acknowledged. On one hand, the narratives have accumulated the perspectives from a wide range of experts' knowledge concerning several types of non-domestic buildings (i.e. higher education, school, museum, hospital, library, and office). On the other hand, there has not been a single case study that combined the complete range of specialisations due to the lack of accessibility. Additionally, for a more detailed evaluation of the effectiveness of the developed BIM-enabled collaborative SBD process, it should have been tested to real life projects and observed the outcomes. However, due to lack of resources, and accessibility to project teams, this exercise was not possible to be realised within the scope of this research project.

8.5. Recommendations for future work

The findings of this study could be the basis for further research in several areas. As discussed in the above Section, further work is needed to establish whether the systematic process developed improves SBD implementation, and to better understand the extent to which it affects in achieving sustainability objectives. To actualise that, more modelling work needs to be conducted in order to determine the scope of tasks (BIM Uses and BIM-based Deliverables), and their requirements for BIM-enabled SBD, for the rest of the RIBA Plan of Work's (2013) stages (i.e. 3 – Developed Design, 4 – Technical Design, 5 – Construction, 6 - Handover and Close Out, and 7 - In Use). Once this task is completed, the process should be tested through practical applications to real life projects so as to examine its long-term efficacy. Nevertheless, in order to ensure the reproducibility and dependability of the research outcomes, the process should also be tested for various types of buildings (such as residential) and for different locations (worldwide). Therefore, considerably more work needs to be done (i.e. action research, usability and functionality testing) for the development of a functioning tool for the workflow management of BIM-enabled SBD, which potentially can assist in the life-cycle management of sustainable buildings. Moreover, it is recommended that further research needs to be undertaken in the following areas so as to proceed towards Level 3 BIM maturity (see Figure 3.1), for SBD: (i) integration with existing BIM and BPA tools along with automation of certain performance evaluation exercises; (ii) integration with existing collaboration platforms and project management tools; (iii) visualisation of day-to-day progress, with carefully consideration of privacy and permissions; (iv) compliance checking towards regulations and reporting, including a scoring system for design criteria.

8.6. Epilogue

This study has been one of the first attempts to systematically define the BIM-enabled SBD process for the early stages. For this purpose, the state of the art advancements of the domain have been examined in order to identify the gaps in existing knowledge. Additionally, a framework of the critical components of SBD (roles, responsibilities, tasks, deliverables, and decision points) has been presented and discussed. Then, the timing and sequencing of the components' sub-categories have been defined into a holistic CE process model. The IDEF process model, developed in this study, coordinates "*bottom-up*" sustainability considerations with "*top-down*" organisation between SBD stakeholders. As a result, the IDEF model can be utilised within a CDE to facilitate the collaborative process at Concept Design stage. Nevertheless, it is acknowledged that a single linear prescribed process is not viable for SBD, because the complexity, amount of specialisation, and individual project needs, do not permit a definition without iterations. As demonstrated by the incidents' narratives, learning from experience can facilitate the creation of a more detailed SBD process model to guide future projects so as to avoid repeating mistakes. Therefore, the results of this research support the idea that a transparent SBD process, which follows specified communication patterns, can assist in achieving sustainability efficiently in terms of time, cost, and effort. Further work, is thus, required to bring this framework, process, and tool into real life projects, where the efficacy of the approach could be tested.

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Appendix A

Publications

Title: Towards a BIM-enabled sustainable building design process: roles, responsibilities, and requirements

Authors: Zanni, Maria A.; Soetanto, Robby; and Ruikar, Kirti

Keywords: Design process; Collaboration; Sustainability; Building information modelling (BIM); Building performance analysis (BPA); Concurrent engineering (CE); Integrated DEFinition methods (IDEF).

Citation: ZANNI, M.A., SOETANTO, R. and RUIKAR, K., 2016. Towards a BIM-enabled sustainable building design process: roles, responsibilities and requirements. Architectural Engineering and Design Management, In Press.

Abstract: Environmental sustainability considerations are often treated as an add-on to building design, following ad hoc processes for their implementation. As a result, the most common problem to achieve a sustainable building outcome is the absence of the right information at the right time to make critical decisions. For design team members to appreciate the requirements of multidisciplinary collaboration, there is a need for transparency and a shared understanding of the process. This research presents the findings from 25 in-depth interviews with industry practitioners concerning 10 case studies of buildings, which achieved high sustainability certification ratings (e.g. BREEAM, Passivhaus, Part L), to identify best practices in sustainable building design (SBD). The results identify the key players' roles and responsibilities, tasks, deliverables and critical decision points for SBD. These components have been coordinated explicitly in a systematic process that utilises Information Communication Technology (ICT), Building Information Modelling (BIM), and Building Performance Analysis (BPA) software to realise the benefits of combining distributed teams' expertise.

DOI: 10.1080/17452007.2016.1213153

URI: https://dspace.lboro.ac.uk/2134/22277

Publisher Link: http://dx.doi.org/10.1080/17452007.2016.1213153

ISSN: 1752-7589

Title: Defining the sustainable building design process: methods for BIM execution planning in the UK

Authors: Zanni, Maria A.; Soetanto, Robby; and Ruikar, Kirti

Keywords: Sustainable building design; BIM; Performance modelling; Assessment methods; RIBA plan of work; Process mapping; Interdisciplinary collaboration.

Citation: ZANNI, M.A., SOETANTO, R. and RUIKAR, K., 2014. Defining the sustainable building design process: methods for BIM execution planning in the UK. International Journal of Energy Sector Management, 8 (4), pp.562-587.

Abstract: Purpose – Building performance analysis is usually performed after the design and construction documents are produced resulting in lost opportunities. The purpose of this research is to develop a BIM-enabled sustainable design process model that identifies critical actions in the design process along with the information and level of detail that facilitate an informed and timely decision. Design/methodology/approach – A number of research methods have been adopted; these include extensive literature review and eleven in-depth interviews with industry practitioners (sustainable building design experts, early BIM adopters). Findings – Project delivery methods have a significant effect on the sustainable outcome of buildings. The development of a structured process can assist sustainable design practice among building professionals. Learning from implemented projects, that have utilised BIM processes, facilitates the scope of creating this process and advises future projects in order to prevent failures. Process mapping is essential to streamline the process, support key project processes and help the design team manage their own responsibilities and deliverables required by them. Originality/value – The identification of the gap and the need for a structured process for sustainable building design for BIM execution is discussed. The synergies that exist between BIM, building performance modelling, BREEAM assessment and the RIBA Plan of Work are shown. The effect that project delivery has on sustainable design outcome has been established. A coordinated collaborative design process model is presented based on the findings from interviewing early adopters.

DOI: 10.1108/IJESM-04-2014-0005

URI: https://dspace.lboro.ac.uk/2134/16500

Publisher Link: http://dx.doi.org/10.1108/IJESM-04-2014-0005

ISSN: 1750-6220

Title: Facilitating BIM-based sustainability analysis and communication in building design process

Authors: Zanni, Maria A.; Soetanto, Robby; and Ruikar, Kirti

Keywords: Sustainability; BIM; Building simulation; Integration; Collaboration; BREEAM.

Publisher: Japan Society of Civil Engineers

Citation: ZANNI, M.A., SOETANTO, R. and RUIKAR, K., 2013. Facilitating BIM-based sustainability analysis and communication in building design process. IN: Proceedings of the 6th Civil Engineering Conference in Asia Region (CECAR6), Jakarta, Indonesia, 20-22 August 2013, 8pp.

Abstract: Population growth and resource scarcity has created unprecedented demand of sustainable buildings around the world. During design and construction processes, meeting this demand is considered an extremely challenging task, at least due to following several reasons. Firstly, the long-term sustainability of a building is difficult to define, let alone assess. Although there are standard assessment methods (e.g. BREEAM, LEED) and specific client requirements, each participant of the process may have different views and approaches to sustainability owing to their disciplinary practices and experiences. Secondly, although the most critical time to make decisions on a building's sustainable features is during the early stages of design, building performance analysis (for relatively easy to agree and accurately predict performance criteria, such as energy efficiency) is usually performed after the design and construction documents are produced. This practice results in lost opportunities to maximise the sustainability of building design and technology options. Thirdly, it is widely documented that the sustainability progress in the AEC/FM industry has been hampered by fragmentation, low innovation, adversarial relationships and slow adoption of Information Communication Technologies. The emergence of Building Information Modelling (BIM) has promised an accelerated progress of sustainable building development. BIM promotes integration among building professionals and improves design goals by allowing multi-disciplinary information to be integrated within a single model. This creates an opportunity to conduct the analysis throughout the design process, concurrently with the production of the design documents. Despite these expected benefits, the practice of using BIM for sustainability has not been widely embedded within the AEC/FM industry. In order to achieve a step change in current processes for optimal results, there is a need to define requirements of the process, tools, systems and stakeholders responsibilities of conducting sustainability assessment during the design stages of a building. To align with the industry practice, this should be based on the recently developed BIM Overlay to the RIBA Outline Plan of Work which offers a response to the UK Government's commitment to have all projects utilising BIM from 2016. This paper presents a comprehensive literature review along with a conceptual model based on the RIBA Plan of Work 2013. The model describes the main stages of the sustainability design process and the key inputs and outputs of each stage.

URI: https://dspace.lboro.ac.uk/2134/14506

Publisher Link: https://wiryanto.files.wordpress.com/2013/08/paper-327.pdf

ISBN: 978-602-8605-08-3

Title: Exploring the potential of BIM-integrated sustainability assessment in AEC

Authors: Zanni, Maria A.; Soetanto, Robby; and Ruikar, Kirti

Keywords: Sustainability; BIM; Building simulation; Integration; Collaboration; BREEAM.

Citation: ZANNI, M.A., SOETANTO, R. and RUIKAR, K., 2013. Exploring the potential of BIM-integrated sustainability assessment in AEC. IN: Soetanto, R. (ed.) Proceedings of the Sustainable Building and Construction Conference (SB13), Coventry, 3-5 July 2013, pp. 186 - 195.

Abstract: Worldwide, the need for designing and constructing more sustainable buildings is constantly growing. Although the most critical time to make decisions on a building's sustainable features is during the early stages of design, building performance analysis is usually performed after the design and construction documents are produced. This practice results in lost opportunities to maximise the use of energy efficient building design and technology options. Along with that, it is widely documented that productivity in the AEC/FM industry has been hampered by fragmentation, low innovation, adversarial relationships and slow adoption of Information Communication Technologies. Building Information Modelling (BIM) can promote integration among building professionals and improve design goals by allowing multi-disciplinary information to be integrated within one model. This creates an opportunity to conduct the analysis throughout the design process, concurrently with the production of the design documents. Despite the expected benefits of BIM and sustainable performance analysis, their practices have not been widely embedded within the UK AEC/FM industry. In order to achieve the change in current processes for optimal results, there is a need to define a number of aspects. These include the drivers, actions, good practices, impacts and benefits of sustainability analysis integration in the BIM-collaborative processes on one hand, and the barriers, limitations and deficiencies of current practice on the other. This paper is an early contribution to this ongoing research to improve the way of conducting BIM-based sustainability analysis and communicating the results among the various AEC participants. This can be achieved by automating and standardising the decision making process at the pre-construction stage. The findings indicate that there is no single tool that can be utilised to assess the full range of criteria required for achieving sustainability. It is also demonstrated how the capabilities of BIM-related sustainability software can be used to predict a number of the BREEAM rating system categories criteria.

URI: https://dspace.lboro.ac.uk/2134/14508

Publisher Link: http://www.coventry.ac.uk/Global/Faculty%20events/SB13/SB13-20-Exploring-the-potential-of-BIM-integrated-sustainability-assessment-in-AEC.pdf

ISBN: 978-1-84600-049-2

Appendix B

Data collection methods and instruments

Ethics Approvals (Human Participants) Sub-Committee

Ethical Clearance Checklist

Has the Investigator read the 'Guidance for completion of Ethical Clearance Checklist' before starting this form?	Choose an item

Does the study require NHS approval? *Please complete a copy of the checklist providing a brief project description in the additional information section. Please send this to the Secretary of the Ethics Approvals (HP) Sub-Committee before starting your NHS application.*	Choose an item

Project Details

1. Project Title: Click here to enter text

Investigator(s) Details

2. Name of Investigator 1: Click here to enter text	10. Name of Investigator 2: Click here to enter text
3. Status: Choose an item	11. Status: Choose an item
4. School/Department: Click here to enter text.	12. School/Department: Click here to enter text.
5. Programme (if applicable): Click here to enter text.	13. Programme (if applicable): Click here to enter text.
6. Email address: Click here to enter text.	14. Email address: Click here to enter text.
7a. Contact address: Click here to enter text.	15a. Contact address: Click here to enter text.
7b. Telephone number: Click here to enter text.	15b. Telephone number: Click here to enter text.
8. Supervisor: Choose an item	16. Supervisor: Choose an item
9. Responsible Investigator: Choose an item	17. Responsible Investigator: Choose an item
List all other investigators (name/email address): Click here to enter text.	

Participants

18. Does the project involve NHS patients from the National Centre for Sport and Exercise Medicine. *NHS approval may be required. Please complete a copy of the checklist providing a brief project description in the additional information section. Please send this to the Secretary of the Ethics Approvals (HP) Sub-Committee.*	Choose an item

Positions of Authority

19. Are investigators in a position of direct authority with regard to participants (e.g. academic staff using student participants, sports coaches using his/her athletes in training)?	Choose an item

Vulnerable groups

20. Will participants be knowingly recruited from one or more of the following vulnerable groups?		
Children under 18 years of age		Choose an item
Persons incapable of making an informed decision for themselves		Choose an item
Pregnant women		Choose an item
Prisoners/Detained persons		Choose an item
Other vulnerable group Please specify: Click here to enter text		Choose an item
If Yes to any of question 20, please answer the following questions:		
	21. Will participants be chaperoned by more than one investigator at all times?	Choose an item
	22. Will at least one investigator of the same sex as the participant(s) be present throughout the investigation?	Choose an item
	23. Will participants be visited at home?	Choose an item

Investigator Safety

24. Will the investigator be alone with participants at any time?		Choose an item
If Yes to question 24, please answer the following questions:		
	24a. Will the investigator inform anyone else of when they will be alone with participants?	Choose an item
	24b. Has the investigator read the Guidance Notes on 'Conducting Interviews Off-Campus and Working Alone' and will abide by the recommendations within?	Choose an item

Methodology and Procedures

25. Please indicate whether the proposed study:	
Involves taking bodily samples (please refer to published guidelines)	Choose an item
Involves using bodily samples previously collected with consent for further research	Choose an item
Involves transporting Human Tissue Act relevant material to or from Loughborough (a materials transfer agreement is required)	Choose an item
Involves procedures which are likely to cause physical, psychological, social or emotional distress to participants	Choose an item
Is designed to be challenging **physically** or **psychologically** in any way (includes any study involving physical exercise)	Choose an item
Exposes participants to risks or distress greater than those encountered in their normal lifestyle	Choose an item
Involves collection of body secretions by invasive methods	Choose an item
Prescribes intake of compounds additional to daily diet or other dietary manipulation/supplementation	Choose an item
Involves pharmaceutical drugs/medicines	Choose an item
Involves use of radiation	Choose an item
Involves use of hazardous materials	Choose an item
Assists/alters the process of conception in any way	Choose an item
Involves methods of contraception	Choose an item
Involves genetic engineering	Choose an item

Involves testing new equipment	Choose an item
Involves testing of medical equipment or devices	Choose an item

Observation/Recording

26. Does the study involve observation and/or recording of participants?	Choose an item
27. **If Yes to question 26,** will those being observed and/or recorded be informed that the observation and/or recording will take place?	Choose an item

Informed consent

28. Will participants give informed consent freely?	Choose an item
29. Will participants be fully informed of the objectives of the study and all details disclosed (preferably at the start of the study but, where this would interfere with the study, at the end)?	Choose an item
30. Will participants be fully informed of the use of the data collected (including, where applicable, any intellectual property arising from the research)?	Choose an item

31. For children under the age of 18 or participants who are incapable of making an informed decision for themselves:	
a. Will consent be obtained (either in writing or by some other means)?	Choose an item
b. Will consent be obtained from parents or other suitable person?	Choose an item
c. Will they be informed that they have the right to withdraw regardless of parental/guardian consent?	Choose an item
d. For studies conducted in schools, will approval be gained in advance from the Head-teacher and/or the Director of Education of the appropriate Local Education Authority?	Choose an item
e. For detained persons, members of the armed forces, employees, students and other persons judged to be under duress, will care be taken over gaining freely informed consent?	Choose an item

Deception

32. Does the study involve deception of participants (i.e. withholding of information or the misleading of participants) which could potentially harm or exploit participants?	Choose an item
If Yes to question 32, please answer the following questions:	
33. Is deception an unavoidable part of the study?	Choose an item
34. Will participants be de-briefed and the true object of the research revealed at the earliest stage upon completion of the study?	Choose an item
35. Will there be an increased physical or emotional risk to participants or investigators when participants are informed of the withholding of information or deliberate deception?	Choose an item

Withdrawal

36. Will participants be informed of their right to withdraw from the investigation at any time and to require their own data to be destroyed?	Choose an item

Storage of Data and Confidentiality

37. Will all information on participants be treated as confidential and not identifiable unless agreed otherwise in advance, and subject to the requirements of law?	Choose an item
38. Will storage of data comply with the Data Protection Act 1998 and the Guidance Note on ‘Data Protection and Storage’?	Choose an item
39. Will any transcripts and video/audio recording of participants be kept in a secure place and not released for any use by third parties?	Choose an item

40. Will video/audio recordings be destroyed within ten years of the completion of the investigation or securely archived if required by funder?	Choose an item
41. Will full details regarding the storage and disposal of any human tissue samples be communicated to the participants?	Choose an item
42. Will research involve the sharing of data or confidential information beyond the initial consent given?	Choose an item
43. Will the research involve administrative or secure data that requires permission from the appropriate authorities before use?	Choose an item

Incentives

44. Will incentives be offered to the investigator to conduct the study?	Choose an item
45. Will incentives by offered to potential participants as an inducement to participate in the study?	Choose an item

Work Outside of the United Kingdom

46. Is research being conducted by investigators travelling outside of the United Kingdom?	Choose an item
If Yes to question 46, please answer the following questions:	
47. Country or countries researcher will travel to for the conduct of the research:	Click here to enter text
48. Is this the investigator's home country?	Choose an item
49. Has a risk assessment been carried out to ensure the physical, emotional and cultural safety of the investigator whilst working outside of the United Kingdom?	Choose an item
50. Have you considered the appropriateness of your research in the country you are travelling to and checked the FCO guidance: https://www.gov.uk/foreign-travel-advice?	Choose an item
51. Is there an increased physical, emotional or cultural risk to investigators outside of the United Kingdom as a result of your research study or has the FCO issued a travel warning?	Choose an item
52. Have you obtained any necessary ethical permission needed in the country you are travelling to?	Choose an item

53. Will any of the participants be outside of the United Kingdom?	Choose an item
54. **If Yes to 53**, is there an increased physical, emotional or cultural risk to participants who are outside of the United Kingdom as a result of taking part in your research study?	Choose an item

Risk Assessment

55. Has a risk assessment been carried out and approved by the School, to ensure the physical, emotional and cultural safety of the investigator and participants involved in the study?	Choose an item

Information and Declarations

Checklist Application Only:
If you have completed the checklist to the best of your knowledge, and not selected any answers marked with an *, # or †, your investigation is deemed to conform with the ethical checkpoints. Please sign the declaration and lodge the completed checklist with your Head of Department/School or his/her nominee.

† Checklist with Additional Information to the Secretary:
If you have completed the checklist and have only selected answers which require additional information to be submitted with the checklist (indicated by a †), please ensure that all the information is provided in detail below and send this signed checklist to the Secretary of the Sub-Committee.

Checklist with Generic Protocols Included:
If you have completed the checklist and selected one or more of the answers marked with this symbol # a full Research Proposal needs to be submitted to the Ethical Approvals (Human Participants) Sub-Committee unless you, or one of the investigators on this project, are a named investigator on an existing Generic Protocol which covers the procedure. Please download the Research Proposal form from the Sub-Committee's web page. **A signed copy of this Checklist should accompany the full proposal to the Sub-Committee.**

If you, or one of the investigators on this project, are using a procedure covered by a generic protocol, please ensure the relevant individuals are on the list of approved investigators for that Generic Protocol. Include the Generic Protocol reference number and a short description of how the proposal will be used at the end of the checklist in the space provided for additional information.

The completed checklist should be lodged with your Head of Department/School or his/her nominee.

* Full Application needed:
If on completion of the checklist you have selected one or more answers which require the submission of a full proposal (indicated by a *), please download the Research Proposal form from the Sub-Committee's web page. **A signed copy of this Checklist should accompany the full Research Proposal to the Sub-Committee.**

Space for Additional Information and/or Information on Generic Proposals as requested:

Click here to enter text.

Insurance

Cover is automatic if the research is within the UK & limited to the following activities:

i. Questionnaires, interviews, focus groups, physical activity/exercise, psychological activity including CBT;
ii. Venepuncture (withdrawal of blood);
iii. Muscle biopsy;
iv. Measurements or monitoring of physiological processes including scanning;
v. Collections of body secretions by non invasive methods;
vi. Intake of foods or nutrients or variation of diet (other than administration of drugs).

All other Research involving human participants, including studies outside of the UK, should be referred to the Insurance Officer along with the completed **Insurance Questionnaire** to arrange cover - which may incur a charge. Early submission is recommended.

For completion by Supervisor

Please tick the appropriate boxes. The study should not begin until all boxes are ticked.

☐ The student has read the University's Code of Practice on investigations involving human participants

☐ The topic merits further research

☐ The student has the skills to carry out the research or is being trained in the required skills by the Supervisor

☐ The participant information sheet or leaflet is appropriate

☐ The procedures for recruitment and obtaining informed consent are appropriate

Comments from supervisor:

Click here to enter text.

Signature of Applicant: Click here to enter text.

Signature of Supervisor (if applicable): Click here to enter text.

Signature of Dean of School/Head of Department or his/her nominee: Click here to enter text.

Date: Click here to enter text.

Email to participants (for recruitment)

Request for Interview - Communication of Sustainability Information and Assessment within BIM-enabled Collaborative Environment

Dear [NAME],

I am a PhD research student at Loughborough University. My research aims to improve the process of sustainable design within BIM-enabled collaborative environment for the benefit of industry practice. The research will examine the processes, tools, systems and stakeholders responsibilities of conducting sustainability assessment during early stages of design.

I understand that your company is undertaking building design, and therefore, would be able to benefit from the research. To allow this, I would like to know your views on the initial findings, and wish to have an interview at your convenience. The interview will take around 30 minutes of your time.

I would be grateful if you could confirm your willingness to participate in an interview (video conference, phone or in person) and let me know a suitable time, if possible, in the next two weeks. Please be assured that the findings will be used for academic purposes and confidentiality will be maintained at all times.

Thank you for considering my request. I look forward to your reply.

Yours faithfully,

Maria-Angeliki Zanni

Research Student
School of Civil and Building Engineering
Loughborough University
Loughborough
Leicestershire LE11 3TU
United Kingdom
M.A.Zanni@lboro.ac.uk

Loughborough University

Communication of Sustainability Information and Assessment within BIM-enabled Collaborative Environment

PARTICIPANT INFORMATION SHEET

The following are the contact details of the researchers involved in the study:

Primary Researcher
Ms Maria-Angeliki Zanni, School of Civil and Building Engineering, Loughborough University, Loughborough, Leicestershire, LE11 3TU, United Kingdom, **Email:** M.A.Zanni@lboro.ac.uk

Supervisor 1
Dr Robby Soetanto, School of Civil and Building Engineering, Loughborough University, Loughborough, Leicestershire, LE11 3TU, United Kingdom, **Email:** R.Soetanto@lboro.ac.uk, **Phone:** +44 (0)1509 228748

Supervisor 2
Dr Kirti Ruikar, School of Civil and Building Engineering, Loughborough University, Loughborough, Leicestershire, LE11 3TU, United Kingdom **Email:** k.d.ruikar@lboro.ac.uk, **Phone:** +44 (0)1509 223774

What is the purpose of the study?
Thank you for agreeing to participate in this study. This research aims to improve the process of sustainable design within BIM-enabled collaborative environment for the benefit of industry practice. The research examines the processes, tools, systems and stakeholders responsibilities of conducting sustainability assessment during the early stages of design.

Who is doing this research and why?
The main researcher is Maria-Angeliki Zanni and is performing the study as part of her PhD research. The supervisors for this research are Dr Robby Soetanto and Dr Kirti Ruikar.

Once I take part, can I change my mind?
Yes! After you have read this information and asked any questions you may have, we will ask you to complete an Informed Consent Form, however if at any time, before, during or after the sessions you wish to withdraw from the study please just contact the main investigator. You can withdraw at any time, for any reason and you will not be asked to explain your reasons for withdrawing. If you require a break during the study, you can do so by informing the researcher.

Will my taking part in this study be kept confidential?
You will only be asked to sign your name on the consent form. For all other written and electronic material, your data will be anonymised. The information provided on the questionnaires will be held by the main researcher for a maximum of six years electronically before being disposed of (conforming to University guidelines). The results will be formed from a thorough analysis of the data you give us in this study. Once the analysis is complete, we intend to publish our findings in a number of conferences. However, any paper will be written with an importance on anonymising any personal data included. All data that is shared with other researchers will be anonymised.

I have some more questions who should I contact?
Any questions you have can be answered by the researcher before, during and after the study. If you have a question once you have left the study, feel free to contact the primary researcher by email at any time (using the contact details at the top of this document). I will aim to issue a response as soon as possible but please allow 48 hours for a response during busy times.

What if I am not happy with how the research was conducted?
The University has a policy relating to Research Misconduct and Whistle Blowing which is available online at http://www.lboro.ac.uk/admin/committees/ethical/Whistleblowing(2).htm.

Loughborough University

Communication of Sustainability Information and Assessment within BIM-enabled Collaborative Environment

INFORMED CONSENT FORM - PARTICIPANT COPY

The purpose and details of this study have been explained to me in the Participant Information Sheet. I understand that this study is designed to further scientific knowledge and that all procedures have been approved by the Loughborough University Ethical Advisory Committee.

I have read and understood the information sheet and this consent form.

I have had an opportunity to ask questions about my participation.

I understand that I am under no obligation to take part in the study.

I understand that I have the right to withdraw from this study at any stage for any reason, and that I will not be required to explain my reasons for withdrawing.

I understand that all the information I provide will be treated in strict confidence and will be kept anonymous and confidential to the researchers unless (under the statutory obligations of the agencies which the researchers are working with), it is judged that confidentiality will have to be breached for the safety of the participant or others.

I agree to participate in this study.

Participant Name ______________________________

Participant Email ______________________________

Participant Signature ______________________________

Researcher Signature ______________________________

Date ______________________________

Loughborough University

Communication of Sustainability Information and Assessment within BIM-enabled Collaborative Environment

INFORMED CONSENT FORM - RESEARCHER COPY

The purpose and details of this study have been explained to me in the Participant Information Sheet. I understand that this study is designed to further scientific knowledge and that all procedures have been approved by the Loughborough University Ethical Advisory Committee.

I have read and understood the information sheet and this consent form.

I have had an opportunity to ask questions about my participation.

I understand that I am under no obligation to take part in the study.

I understand that I have the right to withdraw from this study at any stage for any reason, and that I will not be required to explain my reasons for withdrawing.

I understand that all the information I provide will be treated in strict confidence and will be kept anonymous and confidential to the researchers unless (under the statutory obligations of the agencies which the researchers are working with), it is judged that confidentiality will have to be breached for the safety of the participant or others.

I agree to participate in this study.

Participant Name ______________________________

Participant Email ______________________________

Participant Signature ______________________________

Researcher Signature ______________________________

Date ______________________________

INTERVIEW STRUCTURE

Communication of Sustainability Information and Assessment within BIM-enabled Collaborative Environment

Introductory questions:

1. What is the National Classification for your organization (in terms of size)?
2. What types of construction projects do you usually undertake?
3. What is the size of the projects that you undertake in terms of budget?

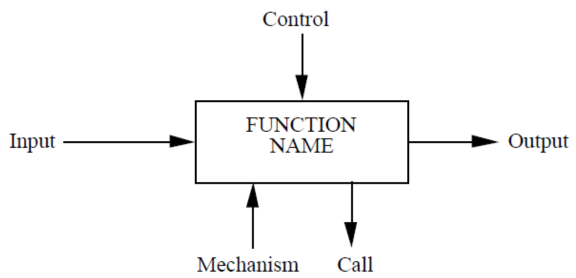
Transitional questions:

4. For how long and to what extend have you been using BIM software? Which one and why have you made that choice?
5. How do you assess sustainability in a project? At which stages? Do you use any particular software for that reason? If yes, which one and why have you made this choice?
6. In what ways have the processes that you collaborate and communicate with the other stakeholders have changed with the use of BIM? Do you follow a defined process to achieve that? Who do you believe that should participate at each stage?
7. What are the main deficiencies that you have identified in your transition towards BIM-enabled sustainable design processes?
8. How has your role changed within BIM collaborative process in regards to the sustainability aspect? Which are your main duties during the design process?

Main questions:

This set of questions is based on the IDEF0 (Integration DEFinition language 0) model created according to the RIBA Plan of Work 2013. The model is using the ICOM (Input, Control, Output, and Mechanism) code:

- Controls - Specifies the conditions required for the function to produce correct outputs.
- Inputs – Something that is transformed or consumed by the function
- Outputs – Data or objects produced by the function
- Mechanism – Means that support the execution of the function
- Call – Support information provided to other functions.



9. Does the A0 diagramme describe the process that you undertake sustainable design? Which are the similarities and differences?
10. Do you believe that it can be incorporated into practice as is? If not, what changes should be made so as to be adopted in current practice?

During the Preparation Stage:

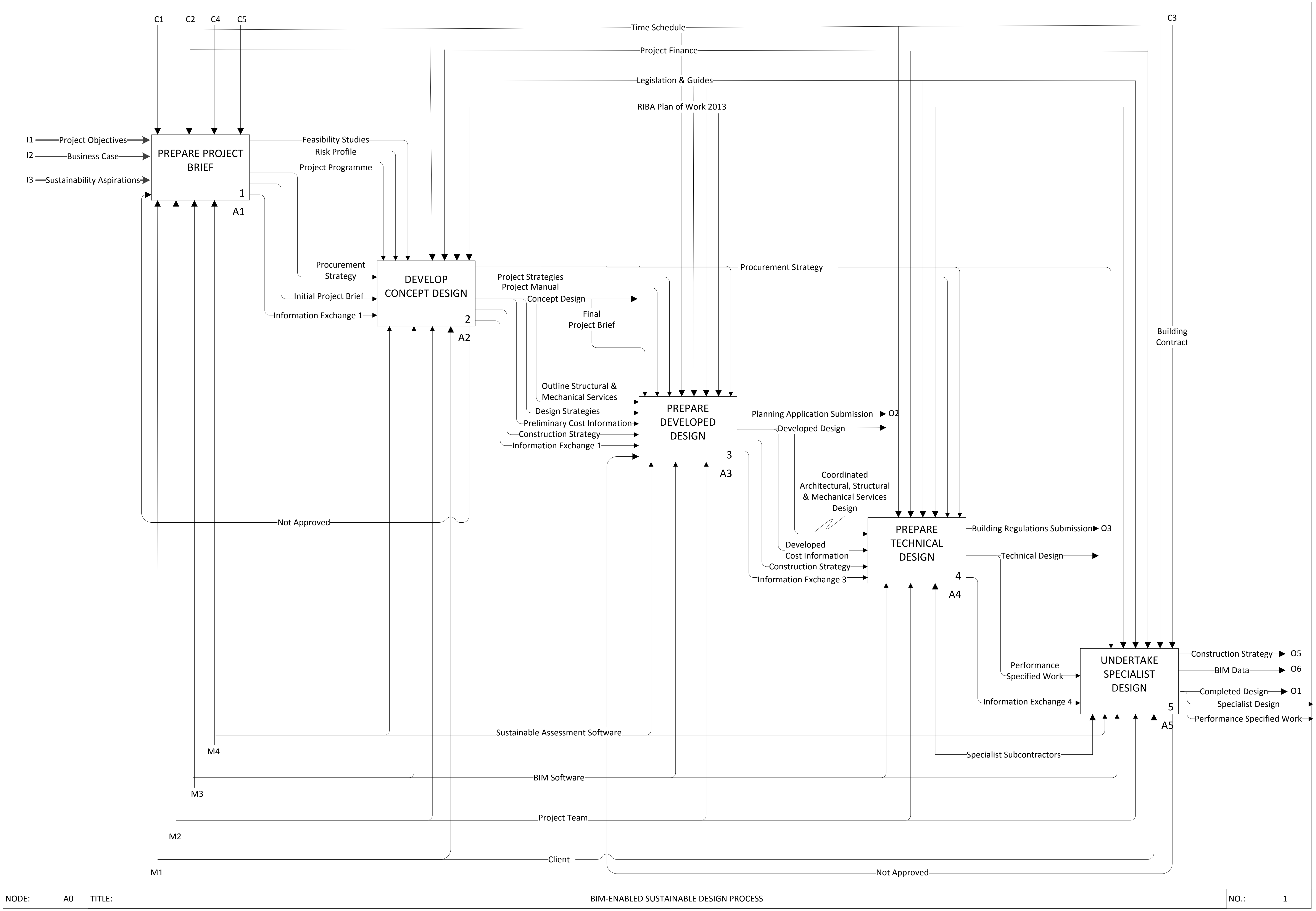
11. What is your role in the design of the Project Brief?
12. Which information do you require and from whom do you acquire this information?
13. How can you define the term “sustainability aspirations”? What kind of information that includes?
14. What is the level of detail required and produced at this stage?

During the Design Development Stages:

15. What kind of sustainability analysis do you undertake? How do you prioritise the sustainability aspects?
16. What information do you require and produce regarding sustainability aspects?
17. With whom do you communicate and how (use of ICT)?
18. What are the formats of the inputs and outputs (CAD drawings, interoperability standards)?
19. What is your interaction with the client throughout this process?

Closing question:

20. In the next five years, which changes should be made in the existing process in order to successfully incorporate the new technology? What is needed and missing to improve the sustainable design process?



C1
C2
C4
C5
C3
Time Schedule
Project Finance
Legislation & Guides
RIBA Plan of Work 2013
I1
Project Objectives
I2
Business Case
I3
Sustainability Aspirations
PREPARE PROJECT BRIEF
1
A1
Feasibility Studies
Risk Profile
Project Programme
Procurement Strategy
Initial Project Brief
Information Exchange 1
DEVELOP CONCEPT DESIGN
2
A2
Project Strategies
Project Manual
Concept Design
Final Project Brief
Procurement Strategy
Outline Structural & Mechanical Services
Design Strategies
Preliminary Cost Information
Construction Strategy
Information Exchange 1
PREPARE DEVELOPED DESIGN
3
A3
Planning Application Submission
O2
Developed Design
Coordinated Architectural, Structural & Mechanical Services Design
Developed Cost Information
Construction Strategy
Information Exchange 3
PREPARE TECHNICAL DESIGN
4
A4
Building Regulations Submission
O3
Technical Design
Building Contract
Performance Specified Work
Information Exchange 4
UNDERTAKE SPECIALIST DESIGN
5
A5
Construction Strategy
O5
BIM Data
O6
Completed Design
O1
Specialist Design
Performance Specified Work
Not Approved
Sustainable Assessment Software
M4
Specialist Subcontractors
BIM Software
M3
Project Team
M2
Client
M1
Not Approved
NODE:
A0
TITLE:
BIM-ENABLED SUSTAINABLE DESIGN PROCESS
NO.:
1

Phase 2. Main data collection – 1st set's questionnaire

Purpose Statement

The purpose of the research is to develop a default sustainable design process model and identify critical decisions in the design process along with the information and level of detail that is associated to make a decision on an accurate basis. The goal is to make explicit what is currently tacit among sustainable design experts and increase understanding of the implications of certain design decisions at the overall design outcome. It is also examined how multi-disciplinary collaboration between stakeholders can assist into achieving a holistic approach to design by considering the trade-off relationships among various aspects of design concurrently. It is argued that learning from experience can facilitate the scope to create a detailed process to advise future projects achieve a more sustainable outcome. The scenario discussed here is about challenging incidents during the design process of an educational building which the goal has been a sustainable outcome.

Topics to be covered

- Design intent
- Critical decisions (outstandingly effective/ineffective)
- Impact to overall result (severity)
- Commonality - probability
- Level of detail of information needed
- People involved
- Methods involved in each decision
- Activities undertaken (types of analysis, considerations, interpretation of results)
- Timing and sequence
- Associated objects
- Prioritisation of design criteria
- Reasoning behind decisions

- Design outcome and assessment (measurable or not)
- Recommendations/ reflection upon decision

Types of information being sought

1. Names of objects
2. Activity names
    - Sequencing and structure
3. Facts and constraints related to process occurrences
    - Constraints that govern the initiation of a process
    - Conditions that must hold during the process
    - Conditions that signal the termination of the process
    - Processes triggered by the initiation or termination of the process
    - Properties of an occurrence of the process (e.g. duration)
    - Objects that participate as agents, information, resources, or products in the process
    - Properties of the objects
    - Relations or constraints on objects between processes (e.g. shared resources)
    - Conditions that must be satisfied relative to the objects participating in the process
    - Distinction between
4. Situation Descriptions
    - Examples from implemented projects (education buildings)
    - Lessons learned (successes and failures, considerations)
    - Occurrence of processes
    - Association of activities with objects
5. Source material
    - Information artifacts of the process (design reports, Gantt charts, meeting minutes)

<u>Basic Procedure</u>

1. **Select incident** to demonstrate non-routine aspects of a domain. Probe components that go beyond the ground knowledge, discriminating the expert. Focus on cases that presented a unique level of challenge for the individual.
2. **Obtain unstructured incident account.** Description of incident: built context, understand unique perspective, activate memory and achieve cooperation.
3. **Construct incident timeline.** Sequence and duration of events.
4. **Decision point identification.** Taking one out of several courses of action or making a judgment that affected the outcome.
5. **Decision point probing.** Elicit details to represent the information that was needed at each event time (or recall prior experiences analogues). Elicit specific goals (&assess) and options for each decision (choices made/rejected). Describe the basis for selecting an option and if a rule was used, should be stated.

<u>Important probes:</u> cues, knowledge, analogues, goals, options, bases for decisions and hypotheticals

<u>Critical decision interview probes</u>

1. Could you recall an incident that you have found challenging (in the design process of an education building regarding sustainability)? (focus on non-routine incidents that have significantly affected the overall outcome & attain general information about project, location, year of completion, size, methods of assessment)
2. Could you provide a description of exactly what happened? (uninterrupted)
3. At which part of the RIBA process (integration to core objectives)? Please create a sequence timeline of events / activities.
4. Which were the critical decision points? Were there any alternative options? What other courses of action were considered by or were available to you?

5. What information did you use in making this decision and how was it obtained? (associate objects with tasks – task analysis of equipment in the design stage / determine activity requirements)
6. What were the sustainable goals at this time?
7. What were the constraints during the process to achieve those goals?
8. Who else was involved in that decision (nominate collaborators/ multidisciplinary perceptions / roles)?
9. What were the criteria for choosing this option? What knowledge was necessary in order to select an option? (What specific training or experience was necessary or helpful in making this decision? Variables that affect the result the most – best case/ worst case scenario / ensure that performance variables are not over or under estimated. How sustainable aspects can be quantified for a holistic approach?)
10. How was this option selected? & other options rejected? What rule was being followed?
11. If the decision was not the best, what training, knowledge or information could have helped?
12. How those have affected the overall outcome (assess)? How would you summarize the situation?
13. How much time pressure was involved in making this decision? (time limit)
14. If a key feature of the situation had been different, what difference would it have made in your decision?

Communication of Sustainability Information and Assessment within BIM-enabled Collaborative Environment

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PhD Researcher

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Loughborough University
Email: M.A.Zanni@lboro.ac.uk

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Workshop Structure

- Introduction
- Problem Definition
- Research Scope

Activity 1: Responses to Section 1 of the Handout

- Theoretical Framework
- Research Process
- Main Findings and Outcomes

Activity 2: Responses to Section 2 of the Handout

- Functionalities of Green BIM Box
- Benefits of Green BIM Box

Activity 3: Responses to Section 3 of the Handout

- Concluding Remarks and Q/A Session

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Introduction

Building Information Modelling

The Government Construction Client Group has mandated fully collaborative Level 2 BIM for its projects by 2016 defined as [1]:

"Managed 3D environment held in separate discipline "BIM" tools with attached data…."

Sustainability

Climate Change Act 2008 [2] requires that emissions are reduced by at least 80% by 2050 compared to 1990 levels.

Operation of buildings account for 40% of global CO^2 emissions [3].

BREEAM® green star LEED BEAM CASBEE®

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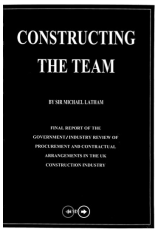
Introduction



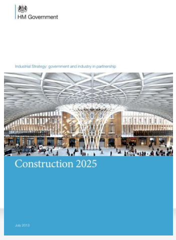
Latham (1994) [4]

National Platform for the Built Environment (2008) [6]

Cabinet Office (2011) [8]

Egan (1998) [5]

Wolstenholme (2009) [7]



HM Government (2013) [9]

Construction industry reports

- The role of the **Project Manager** may take many forms [4]
- Lack of **innovation** in the construction industry [5]
- Success of the construction industry depends on the **efficient creation** and reuse of **information** [6]
- Need for adoption of new **business models** that promote **sustainability** [7]
- Fully collaborative **Level 2 BIM** mandate for government projects by 2016 [8]
- Vision for the UK construction industry: qualified **people**, efficient **technological advanced solutions**' implementation, and **sustainable**, **low-carbon** and **green** construction exports [9]

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Problem Definition
technology
iterative
collaboration
BIM
tasks
Sustainable
Design
complex
multidisciplinary
information
non-linear
Building
ICT
Process
communication
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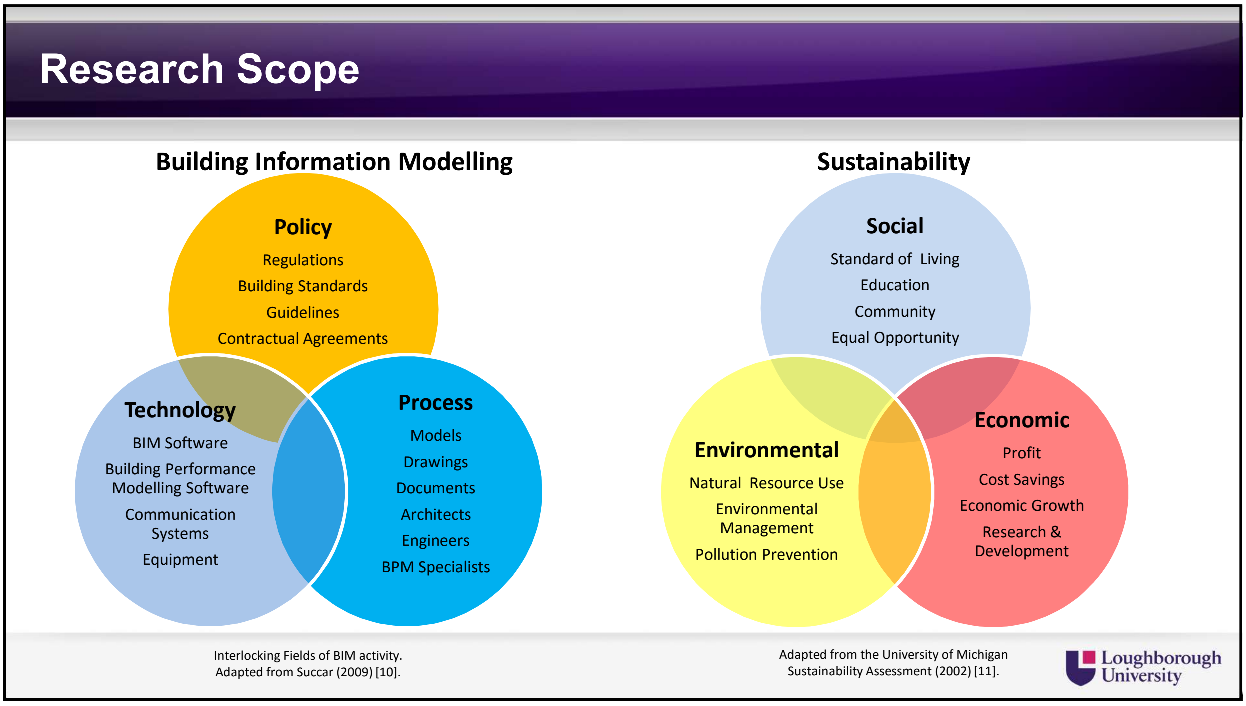
Research Scope
Building Information Modelling
Policy
Regulations
Building Standards
Guidelines
Contractual Agreements
Technology
BIM Software
Building Performance Modelling Software
Communication Systems
Equipment
Process
Models
Drawings
Documents
Architects
Engineers
BPM Specialists
Sustainability
Social
Standard of Living
Education
Community
Equal Opportunity
Environmental
Natural Resource Use
Environmental Management
Pollution Prevention
Economic
Profit
Cost Savings
Economic Growth
Research & Development
Interlocking Fields of BIM activity. Adapted from Succar (2009) [10].
Adapted from the University of Michigan Sustainability Assessment (2002) [11].
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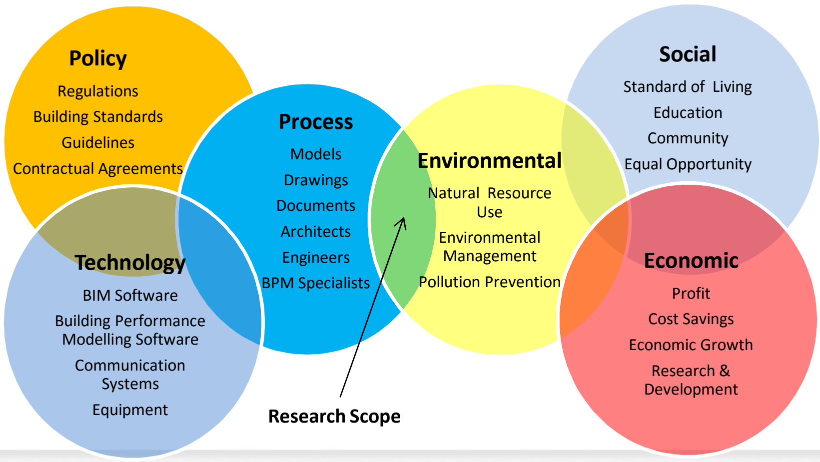
Research Scope

Building Information Modelling + Sustainability



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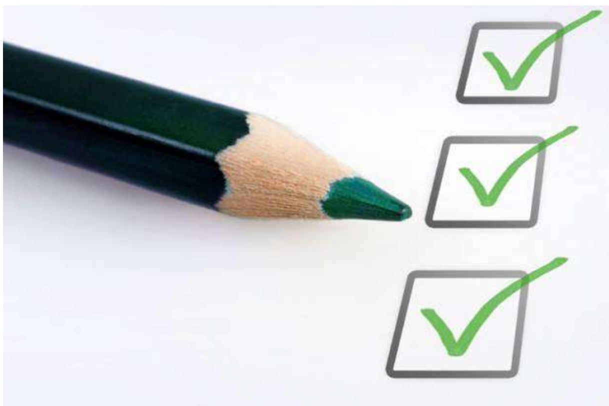
Activity 1: Responses to Section 1 of the Handout



Please respond to Questions 1 to 8 of the Questionnaire Handout

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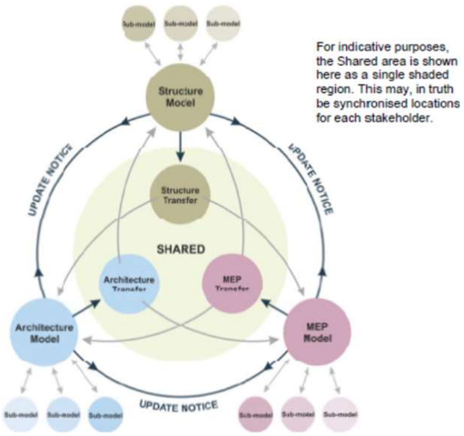
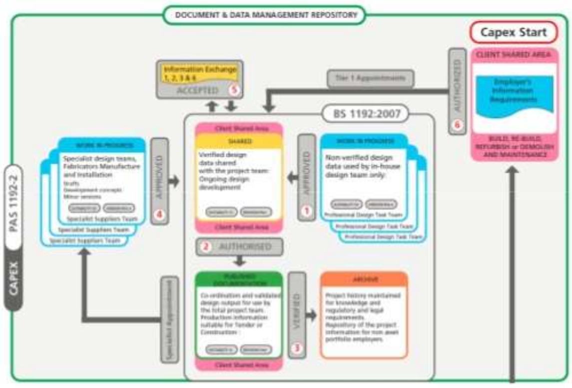
Theoretical Framework



Common Data Environment (CDE) [13]



BS1192:2007 and PAS1192:2-2013

Online Collaboration Platforms (OCPs):
enable both the synchronous and asynchronous collaboration needed in BIM collaborative processes (Anumba, 2002) [12].

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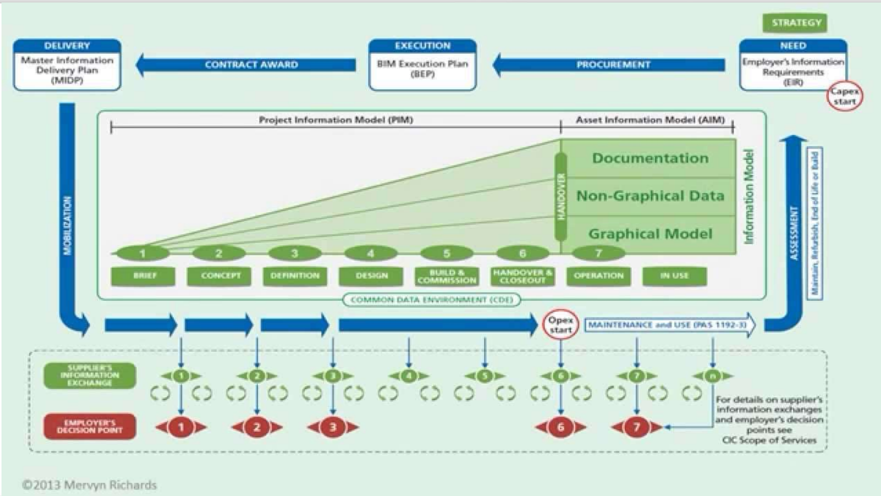
Theoretical Framework



The Information Delivery Cycle, as seen in PAS 1192-2: 2013. © 2013 The British Standards Institution, Mark Bew MBE and Mervyn Richards OBE [13].

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Theoretical Framework

General Systems Theory [14] **:**

"An entity, conceptual or physical, which consists of interdependent parts. Each of the system's elements is connected to every other elements, directly or indirectly, and no sub-set of elements is unrelated to any other sub-set." [15]

University of Salford's Generic Design and Construction Process Protocol (GDCPP) [20]

Computer Integrated Construction (CIC) Research Program's BIM Execution Planning Guide [21]

- Iterative nature of design [16]
- Descriptive design model [17]
- Concurrent Engineering processes [18]
- Adaptive workflow for flexibility [19]

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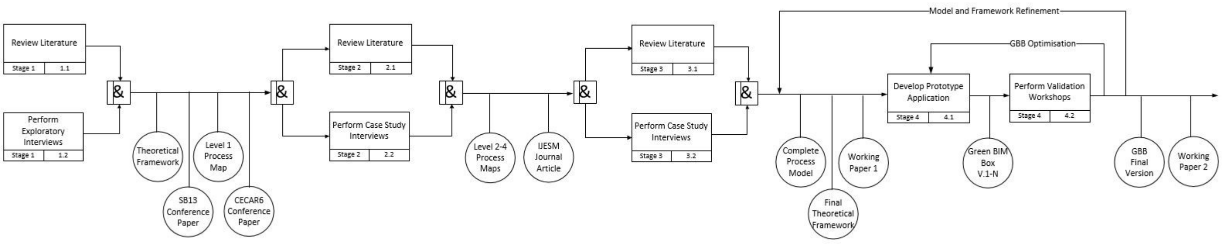
Research Process



Selection criteria of participants:

- Education
  [Architecture, Engineering, Environmental Physics, Sustainable Design]
- Varying industry experience
  [5 to 25+ years]
- Involved in awarded projects
  [CIBSE Building Performance Award, UK Passivhaus Awards, RIBA Sustainability Award, BREEAM (Outstanding or Excellent), & Sustainable Project of the Year]
- Part of organisation with BIM adoption policy
  [Level 2 maturity]

Data collection summary:

- 3 years of data collection
- 25 interviews with industry experts
- 15 organisations (best practices)
- 10 case studies
- 20 incidents narratives
  [examining roles and responsibilities, resources, information exchanges, interdependencies, timing and sequence of events, decision points]
- 24 hours of recorded material
- Reports and documents

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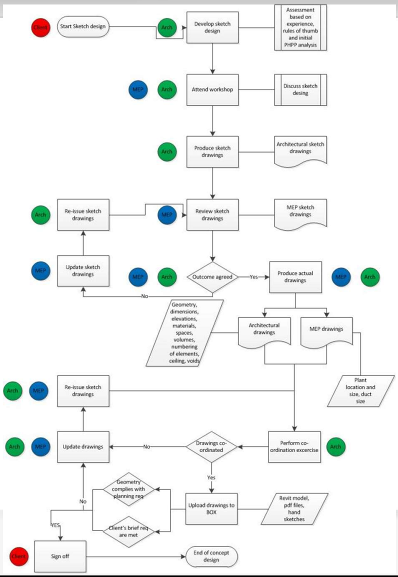
Main Findings and Outcomes



Incident CS3-I06: Preliminary design process to determine building form.

1. Develop building form (Architect)
   Perform preliminary PHPP analysis (Architect)
2. Issue drawings in CDE (Architect)
3. Review drawings (MEP Engineer)
   Assess environmental performance (MEP Engineer)
4. Amend architectural proposal (Architect)
5. Assess environmental performance (MEP Engineer)
6. Agree on design proposal (Architect, MEP Engineer)
7. Develop systems proposal (MEP Engineer)
8. Perform coordination exercise (Architect, MEP Engineer)
9. Approve design proposal (Client)
10. Develop BIM Architecture model (Architect)
11. Issue BIM Architecture model (Architect)
12. Review Architectural Proposal (Design Team)
13. Attend meeting (Design Team)
14. Develop design proposals (Design Team)
15. Agree on design proposals (Design Team)
16. Review design proposal (Client)
17. Sign off concept design stage (Client)

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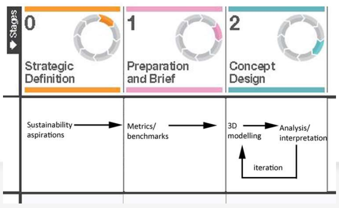
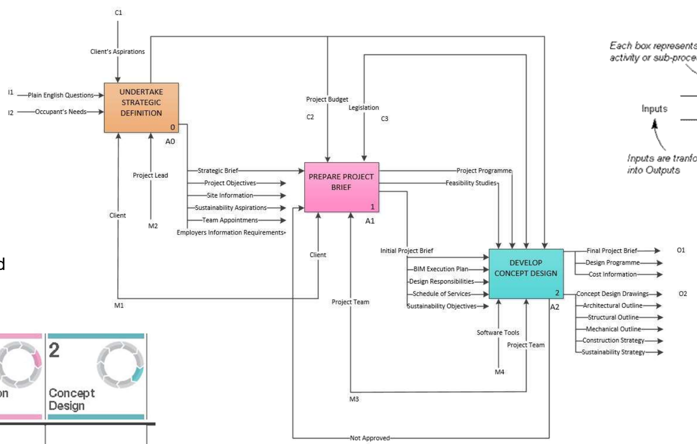
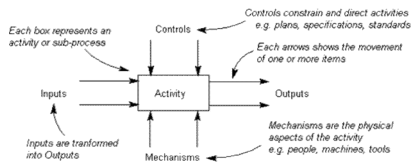
Main Findings and Outcomes

Sustainability considerations aligned with the RIBA Plan of Work 2013 [22]







IDEF0 (Integration DEFinition language) [23] Level 1 of process model

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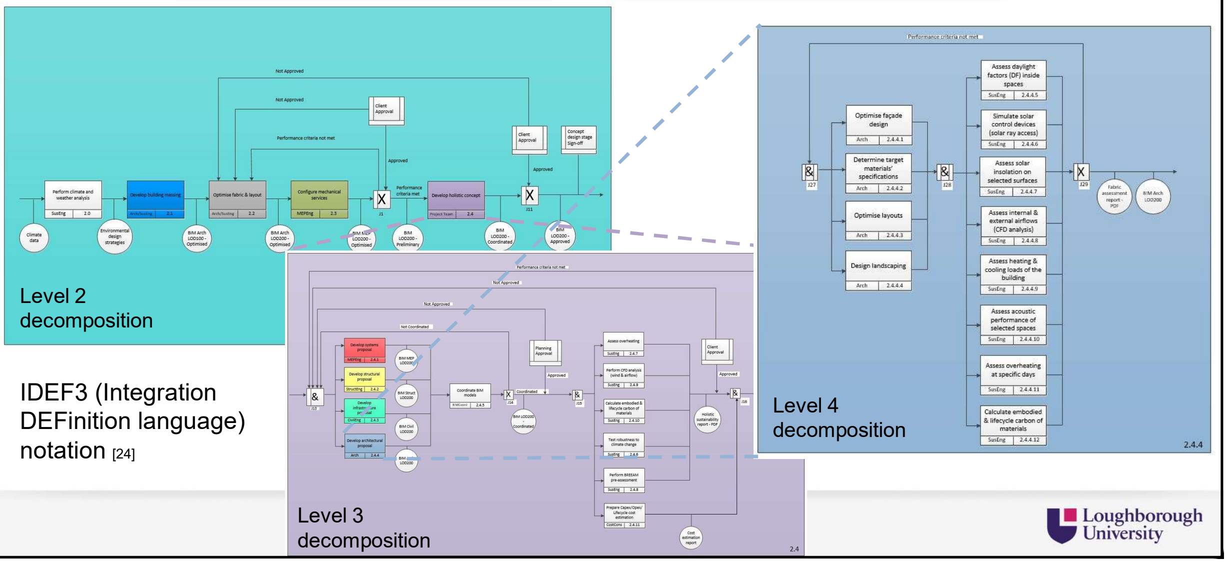
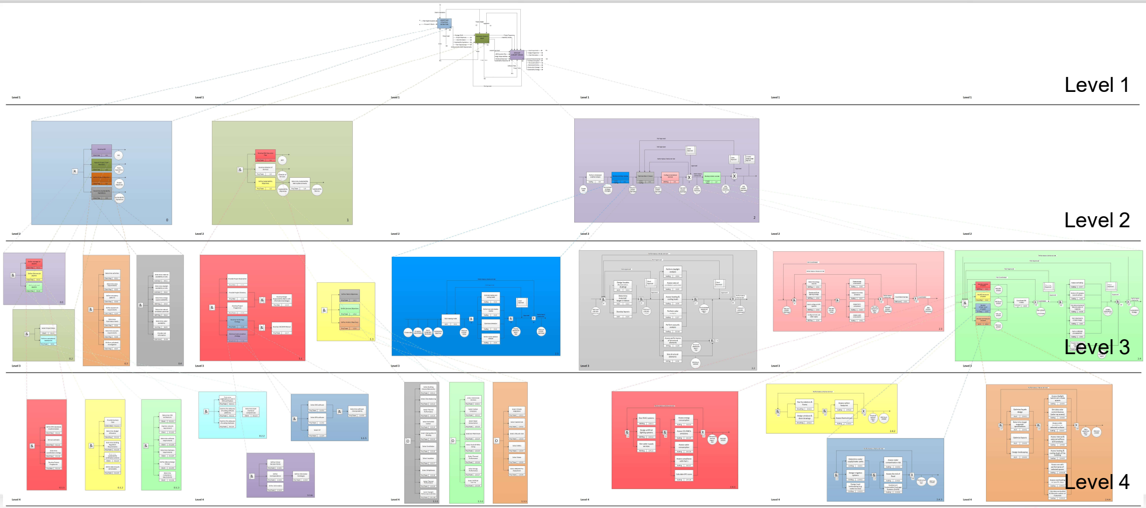
Main Findings and Outcomes



IDEF3 (Integration DEFinition language) notation [24]

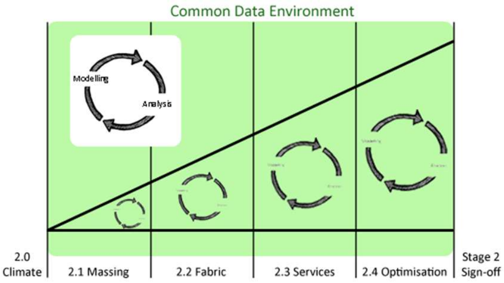
Main Findings and Outcomes



Hierarchical structure of the process model for Concurrent Engineering (CE)

Main Findings and Outcomes

Soft-gates of concept design development for sustainability (Stage 2)



Traditional building design process

Develop Architectural Proposal → Develop Structural Proposal → Develop Systems Proposal → Analyse Building Performance

Concurrent sustainable building design process

Agree Sustainability Objectives → Build Outline Architectural Proposal → Develop Outline Structural Proposal → Develop Outline Systems Proposal

Advice Overall Design Strategy → Assess Outline Proposal Performance → Assess Building Performance

Project Team Roles

Architect	MEP Engineer	Structural Engineer	Sustainability Engineer	Project Team

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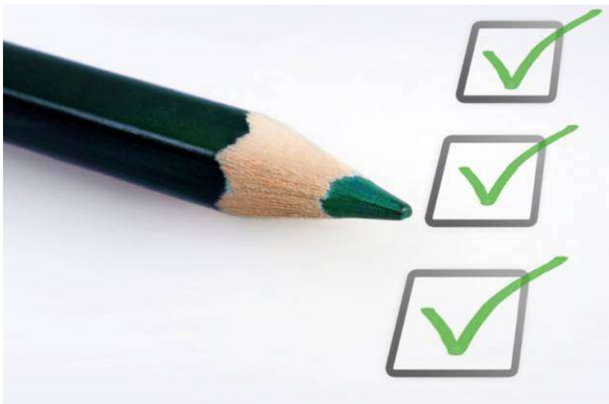
Activity 2: Responses to Section 2 of the Handout



Please respond to Questions 9 to 18 of the Questionnaire Handout

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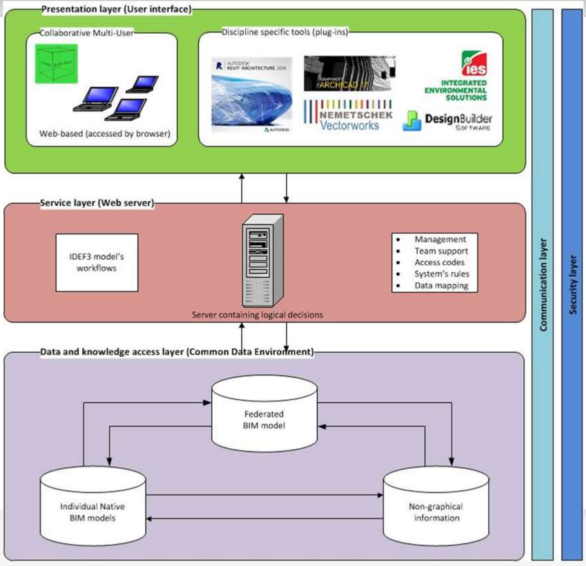
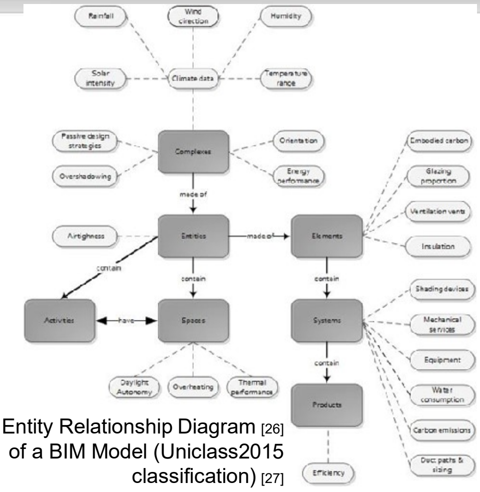
Functionalities of Green BIM Box





Entity Relationship Diagram [26] of a BIM Model (Uniclass2015 classification) [27]

Green BIM Box three-layered system architecture [25]

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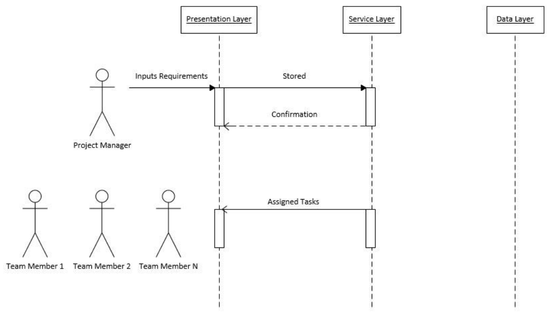
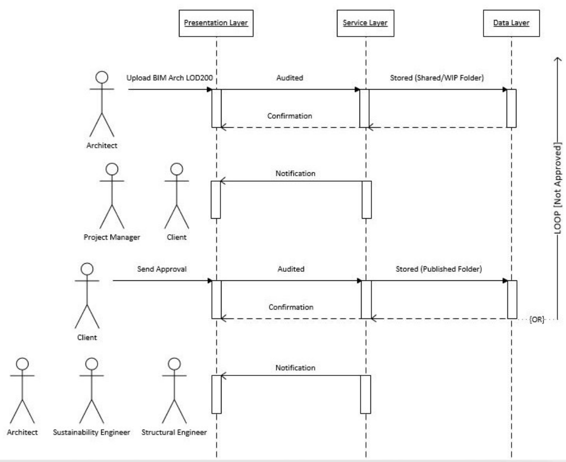
Functionalities of Green BIM Box

Use Case Scenario – Strategic Planning and Briefing



Use Case Scenario – Building Fabric (Phase 1)



Sequence Diagrams demonstrating the system's behaviour
Object Management Group's Unified Modeling Language (OMG UML) [28]

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Functionalities of Green BIM Box

Presentation Layer mock-up in Lumzy prototyping tool [29]
Plug-in Revit software (Autodesk, 2006) [30]

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Benefits of Green BIM Box

- **Comprehensive planning** and **briefing** for sustainability (EIR, BEP)
- **Centralised information** (data and knowledge) management - Automatic document **coordination**
- **Transparent design process** and progress with **defined tasks** and **deliverables** – **Alignment**
- Audit trail for **communication** and **information exchanges**
- **Consistency** through **standardisation** of repeatable process – **Automation** of repeatable process
- **Versioning** on the cloud with automatic **reminders** and **updates**
- **Sustainability** considerations integrated from the beginning - **Quality Assurance**
- **Commitment** to objectives – Track **liability** and export to attach to contracts - **Risk Control**
- Establishing **contribution** of roles towards sustainability – **Compensation** for contribution
- Realistic **project programmes** for front loaded-design – Informed decisions for setting **milestones**
- **Multiparty collaboration** – Iterative process for design **optimisation**
- Streamlining information access and retrieval – **Web-based** application with BIM and BPA software **plug-ins**

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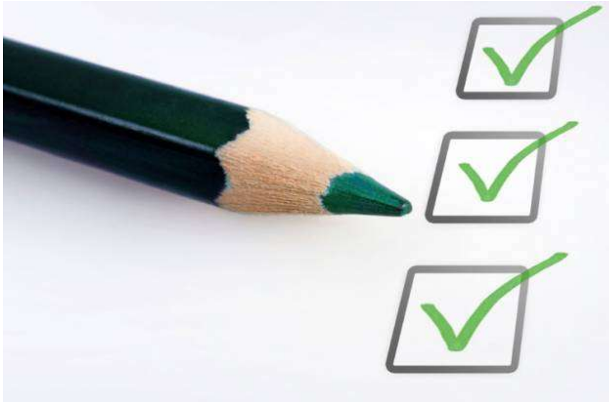
Activity 3: Responses to Section 3 of the Handout



Please respond to Questions 19 to 30 of the Questionnaire Handout

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List of Publications

Peer Reviewed Journal Articles:

- Maria-Angeliki Zanni , Robby Soetanto , Kirti Ruikar , (2014) "Defining the sustainable building design process: methods for BIM execution planning in the UK", International Journal of Energy Sector Management, Vol. 8 Iss: 4, pp.562 – 587.

Refereed Conference Papers:

- Zanni, M.A., Soetanto, R. and Ruikar, K., 2013. Facilitating BIM-based sustainability analysis and communication in building design process. IN: Proceedings of the 6th Civil Engineering Conference in Asia Region (CECAR6), Jakarta, Indonesia, 20-22 August 2013, 8pp.
- Zanni, M.A., Soetanto, R. and Ruikar, K., 2013. Exploring the potential of BIM-integrated sustainability assessment in AEC. IN: Proceedings of the Sustainable Building and Construction Conference (SB13), Coventry, 3-5 July 2013, pp. 186 - 195.

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Concluding Remarks and Q/A Session

Thank you

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Questionnaire Handout

Name:
Organisation:

Start of Section 1 (Questions 1 to 8)

1. *Please select your **role/s** in this organisation (select all that apply):*

- ☐ Client/Client Adviser
- ☐ Landscape Architect/Ecologist
- ☐ Structural Engineer
- ☐ Geotechnical Engineer
- ☐ Cost Consultant
- ☐ Sustainability Lead/Consultant
- ☐ Lighting Engineer
- ☐ BREEAM/Passivhaus Assessor
- ☐ Public Health Consultant
- ☐ Other (specify): ....
- ☐ Architect/Lead Designer
- ☐ MEP Engineer
- ☐ Civil Engineer
- ☐ Transport consultant
- ☐ Contractor
- ☐ Sustainability Engineer
- ☐ Energy Modeller
- ☐ Acoustician
- ☐ BIM Manager/Coordinator

2. *Please select your **educational background** (select all that apply):*

- ☐ Bachelor in (specify): ....
- ☐ Master in (specify): ....
- ☐ Doctorate in (specify): ....
- ☐ Other (specify): ....

***Areas of expertise** (select all that apply):*

- ☐ Architecture
- ☐ Engineering
- ☐ Environmental Physics
- ☐ Sustainability
- ☐ Other (specify): ....

3. *Please state your **professional experience** in sustainable building design (years/months):*

Questionnaire Handout

4. *Please specify your **experience** with sustainable building design (e.g. activities undertaken):*

5. *Please select the **Building Information Modelling (BIM)** software tools that you have utilised for building design (select all that apply):*

- ☐ Autodesk Revit
- ☐ Bentley MicroStation
- ☐ Bentley AECOsim
- ☐ Graphisoft ArchiCAD
- ☐ Nemetschek Vectorworks
- ☐ Autodesk Navisworks
- ☐ Nemetschek Solibri
- ☐ Rhino3D
- ☐ Trimble SketchUp
- ☐ None
- ☐ Other (specify): …………………

6. *Please state your **experience** (years/months) with **Building Information Modelling** (BIM):*

7. *Please select what best describes the **BIM Level of Maturity** that you implement during collaborative building design:*

☐ Level 0 - 2D CAD drafting only is utilised. Output and distribution is via paper or electronic prints, or a mixture of both.

☐ Level 1 - A mixture of 3D CAD for concept work, and 2D for drafting of statutory approval documentation. Electronic sharing of data is carried out from a common data environment (CDE).

☐ Level 2 - All parties use their own 3D CAD models, but not necessarily working on a single, shared model. Design information is shared through a common file format such as IFC (Industry Foundation Class) or COBie (Construction Operations Building Information Exchange). Data are combined in order to make a federated BIM model.

☐ Level 3 - All disciplines use a single, shared project model which is held in a centralized repository. All parties can access and modify that same model.

8. *Please select (by ticking the relevant boxes) the **sustainability compliance schemes** that you utilise to certify sustainability in building design:*

☐ Part L of Building Regulations

☐ Energy Performance Certificate (EPC)

☐ Display Energy Certificates

☐ BREEAM (Building Research Establishment Environmental Assessment Methodology)

☐ LEED (Leadership in Energy and Environmental Design)

☐ Passivhaus or 'Passive House'

☐ CDM (Construction Design Management)

☐ SBEM (Simplified Building Energy Model)

☐ English Heritage

☐ Other (specify): ……………………………………

☐ None

End of Section 1 (Questions 1 to 8)

Start of Section 2 (Questions 9 to 18)

Questionnaire Handout

9. *Please complete the table with **numbers** (1-5) to **rank the frequencies** (1=most, 5=least) that you utilise the following means of communication for information exchanging during collaborative building design:*

	Common Data Environment (CDE)	**Email**	**Telephone**	**Video Conference**	**Meeting**	**Other (specify): ………………..**
2D/3D drawings						
Digital models (BIM)						
Specifications						
Reports						
Images/photographs						
Comments/annotations						
Other (specify): …………………………………..						

10. *Please select (by ticking the relevant boxes) the **Online Collaboration Platforms (OCPs)** that you utilise for exchanging information during collaborative building design:*

- ☐ BOX
- ☐ Conject
- ☐ Viewpoint
- ☐ Autodesk 360 Glue
- ☐ TeamBinder
- ☐ Asite's Adoddle
- ☐ Dropbox
- ☐ Clearbox
- ☐ Sarcophagus
- ☐ IES TaP
- ☐ TrackerPlus
- ☐ BRE SMARTWaste
- ☐ DESTINI Profiler
- ☐ Onuma System
- ☐ Causeway
- ☐ PORTFOLIO Prime
- ☐ Private Extranet
- ☐ None
- ☐ Other (specify): ……………………………………………

11. *Please select (by ticking the relevant boxes) the **standards** that you utilise during BIM implementation:*

- ☐ RIBA Plan of Work 2013 – RIBA Toolkit
- ☐ BS 1192:2007 (Collaborative production of architectural, engineering and Construction information)
- ☐ PAS 11922: 2013 (Specification for information management for the capital/delivery phase of construction projects using building information modelling)
- ☐ CIC Building Information Model (BIM) Protocol
- ☐ GSL (Government Soft Landings)
- ☐ Digital Plan of Work (NBS BIM Toolkit)
- ☐ Classification - Uniclass2015
- ☐ Other (specify): ……………………………………………
- ☐ None

Questionnaire Handout

12. *Please select (by ticking the relevant boxes) the* ***RIBA Plan of Work 2013 Stages*** *that* ***you participate*** *during sustainable building design (select all that apply)**:***

- ☐ 0 – Strategic Definition
- ☐ 1 – Preparation and Brief
- ☐ 2 – Concept Design
- ☐ 3 – Developed Design
- ☐ 4 – Technical Design
- ☐ 5 – Construction
- ☐ 6 – Handover and Close
- ☐ 7 – In Use
- ☐ None

13. *Please state* ***your attitudes*** *towards the following statements (by ticking the relevant boxes):*

	Strongly Disagree	**Disagree**	**Neutral**	**Agree**	**Strongly Agree**
The sustainability criteria need to be set before the design commences.					
The sustainability criteria need to be re-examined after the design synthesis and evaluation happens.					
Trial and error iterations of modelling and analysis optimise the sustainable building design outcome.					
A concurrent engineering process can integrate the sustainability criteria and assessment effectively during multidisciplinary collaborative design.					
A standardised approach to multidisciplinary collaborative sustainable building design increases the possibility to achieve sustainability objectives.					
Automation of repeatable processes can accelerate design tasks.					
A dynamic flexible process is needed for the effective management of organisational workflows during sustainable building design.					

Questionnaire Handout

14. *Please select (by ticking the relevant boxes), the **questions** that you ask the Client so as to define the **project's requirements** during Strategic Definition (Stage 0):*

☐ What activities are going to take place in the building? What are their requirements?
☐ What are the functions of the building? What is their operating schedule?
☐ How many people are going to occupy each area the building?
☐ What equipment is going to be utilised at each space?
☐ What are the specialised needs of the occupants?
☐ What are the illuminance levels required for each activity?
☐ What are the acoustic requirements for each activity?
☐ Are there any sources of volatile organic compounds (VOCs) and toxins in the building or site?
☐ None of the above.

Please list the additional and/or missing questions in the box below:

15. *Please select (by ticking the relevant boxes), the **questions** that you ask the Client so as to define the **sustainability aspirations** during Strategic Definition (Stage 0):*

☐ Is the site's location set? What is the site's climate, topography, surroundings, and transport?
☐ What materials (raw and reusable) are available in or close to the site?
☐ What are the energy sources (e.g. grid, renewables) available at the site?
☐ What is the water availability and quality at the site?
☐ What is the ecology (e.g. wildlife and vegetation) at the site?
☐ Is there risk of flood at the site?
☐ Is it feasible to implement Sustainable drainage systems (SuDS)?
☐ None of the above.

Please list the additional and/or missing questions in the box below:

Questionnaire Handout

16. *Please select (by ticking the relevant boxes), the **milestones** that you set with other team members during sustainable building design implementation (for Stages 0, 1, and 2 of the RIBA Plan of Work 2013):*

- ☐ Climate and weather analysis
- ☐ Optimisation of building massing
- ☐ Optimisation of fabric and layout (passive design strategies)
- ☐ Configuration of mechanical services
- ☐ Coordination of BIM models
- ☐ Planning approval
- ☐ Client approval
- ☐ Design stage sign-off (Stages 0, 1, and 2)
- ☐ None of the above

Please list additional design milestones in the box below:

17. *Please select (by ticking the relevant boxes) the **sustainability criteria** that you consider at Stage 1 (Preparation and Brief) along with their **priorities** towards sustainability:*

	Sustainability Criteria	**Priority**		
		Low	**Medium**	**High**
Fabric	☐ Overshadowing			
	☐ Building height and footprint			
	☐ Embodied carbon of materials			
	☐ Toxicity of materials			
	☐ Recycled materials			
	☐ Glazing and shading			
	☐ Daylighting			
	☐ Insulation (U-Values, W/m²K)			
	☐ Airtightness (at 50Pa)			
	☐ Ventilation and free cooling			
	☐ Overheating			
	☐ Acoustic performance			

Questionnaire Handout

	Sustainability Criteria	Priority		
		Low	Medium	High
Services	☐ Energy consumption			
	☐ Heating, cooling, and hot water			
	☐ Electrical load			
	☐ IT and small power consumption			
	☐ Carbon/CO_2 emissions			
	☐ Energy source			
	☐ Artificial lighting			
	☐ Water consumption			
Holistic	☐ Controls and metering			
	☐ Capital cost – Lifecycle cost			
	☐ Life Cycle Assessment (LCA)			
	☐ Occupancy & user feedback			
	☐ Robustness to climate change			

Please list additional sustainability criteria in the box below (along with their priority):

18. *Please complete the table with the **Building Performance Analysis (BPA)** software tools that* you *utilise to assess sustainability. Specify the **information exchange format** that you share with other project team members during collaborative design.*

	BPA tools (please specify version)	Exchange format/s
<u>**Climate and weather**</u> (e.g. Revit, Sefaira, IES-VE, DesignBuilder, EcoDesigner, TAS, Hevacomp, ESP-r, TRNSYS, Climate Consultant)		
<u>**Massing**</u> (e.g. Revit, Sefaira, EnergyPlus, PHPP, iSBEM, eQuest)		
<u>**Fabric**</u> (e.g. Revit, Sefaira, IES-VE, DesignBuilder, PHPP, EcoDesigner, EDSL TAS Bentley Hevacomp, ESP-r, TRNSYS, Radiance, Daysim, Rapier, EnergyPlus)		

Questionnaire Handout

	BPA tools (please specify version)	Exchange format/s
Services (e.g. Revit, Sefaira, IES-VE, DesignBuilder, PHPP, EcoDesigner, EDSL TAS Bentley Hevacomp, ESP-r, TRNSYS, Radiance, Daysim, Rapier, EnergyPlus, Modelica)		
Renewables (e.g. IES-VE, DesignBuilder, EnergyPlus, Biomass Scenario Model, PVWatts®, Solar and Wind Energy Resource Assessment (SWERA) Model, Geothermal Prospector, Solar Deployment System (SolarDS))		
Life Cycle assessment (LCA) (e.g. Athena, EcoCalculator, SimaPro L, TEAM™, Umberto, SMART Waste, WISARD™, openLCA)		
Cost (CAPEX, OPEX) (IES-VE, Economic Input-Output (EIOLCA), Building Life-Cycle Cost (BLCC), HCSS HeavyBid, Viewpoint MEP Estimating, B2W Estimate, PlanSwift, PrebuiltML, FastPIPE & FastDUCT, Sage Estimating, McCormick Estimating Software, SharpeSodt Estimator, ConEst IntelliBid, ProEst Estimating, WinEst, STACK Estimating)		

Questionnaire Handout

End of Section 2 (Questions 9 to 18)

Start of Section 3 (Questions 19 to 30)

Please tick the relevant boxes:

	Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
19. Is GBB easy to understand and navigate?					
20. Is GBB expressing the needs of BIM-enabled sustainable building design?					
21. Is GBB effective in facilitating the integration of sustainability considerations at the appropriate time during building design?					
22. Is GBB effective in engaging the right people at the right time to achieve sustainability objectives?					
23. Is GBB effective in managing the workflow of the multidisciplinary project team to produce a sustainable outcome?					

Questionnaire Handout

Please comment on the following:

24. Which aspects of GBB have you found to be the most effective? Why?	
25. Which aspects of GBB have you found to be the least effective? Why?	
26. What do you believe are the benefits of using GBB?	
27. Are the categories and their contents expressed in a satisfactory way? What changes would improve understanding?	
28. Would you add or remove any of the categories or their contents? Which ones and why?	
29. In what ways can GBB be improved?	
30. Would you use and/or recommend the use of GBB in the future? Why?	

Questionnaire Handout

Please summarise your views about Green BIM Box:

End of Section 3 (Questions 19 to 30)

Please enter your contact details (email and phone number) in the box below if you are willing to provide additional information to your responses:

Thank you for your participation

Workshop Evaluation

Name:
Organisation:

Please tick the relevant boxes:

	Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
1. The workshop objectives were clearly spelt out.					
2. The workshop was easy to follow and understand.					
3. The presentation was comprehensive and conveyed ideas effectively and clearly.					
4. The questionnaire was well organized and the language was clear and concise.					
5. The pace of this workshop was appropriate.					

Please comment on the following:

6. What was the most effective aspect of the workshop?	
7. What could have been done to improve the workshop?	

Workshop Evaluation

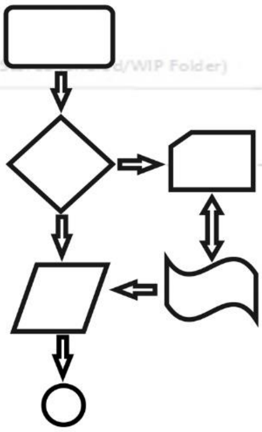
Additional comments or suggestions:

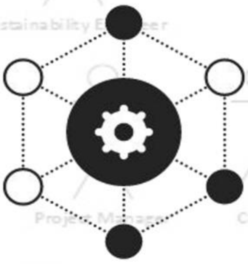
Thank you for your participation

Workflow management for BIM-enabled sustainable building design

Transparent design process

provides visual representation of design workflows for sustainability. Facilitates communication, approval, and tracking of data and interactions within a common data environment (CDE).





Automation of task sequences

enables the envisioned process to be realised. Structured workflows facilitate streamlined multi-party collaboration and integration of deliverables.

Business rules and criteria

evaluate the data and trigger next steps. Process branching allows parallel activities. Customisable rules allow extension of functionality.

Maria-Angeliki Zanni; DipArch/MArch, MSc.
Doctoral Researcher, School of Civil and Building Engineering
Email: M.A.Zanni@lboro.ac.uk

Loughborough University

Process model notation

The model has been constructed utilising the IDEF0 and IDEF3 process notations (see Figure 1). The IDEF0 method uses the ICOM (Input, Control, Output, and Mechanism) (KBSI, 1993)[1]. In IDEF3, the boxes represent real world processes as happenings; those are referred to as units of behaviour (UOB). The arrows that connect the boxes indicate precedence between actions. The junctions represent constraints and enable process branching. The junctions involve choices among multiple parallel or alternative sub-processes. The logical decisions include: and (&), or (O), exclusive or (X), and synchronous or asynchronous start and finish of the processes. The objects are represented as circles that show their different states connected with arrows that have UOB's referents to indicate the entry, transition, state and exit conditions (Mayer et al., 1995).[2]

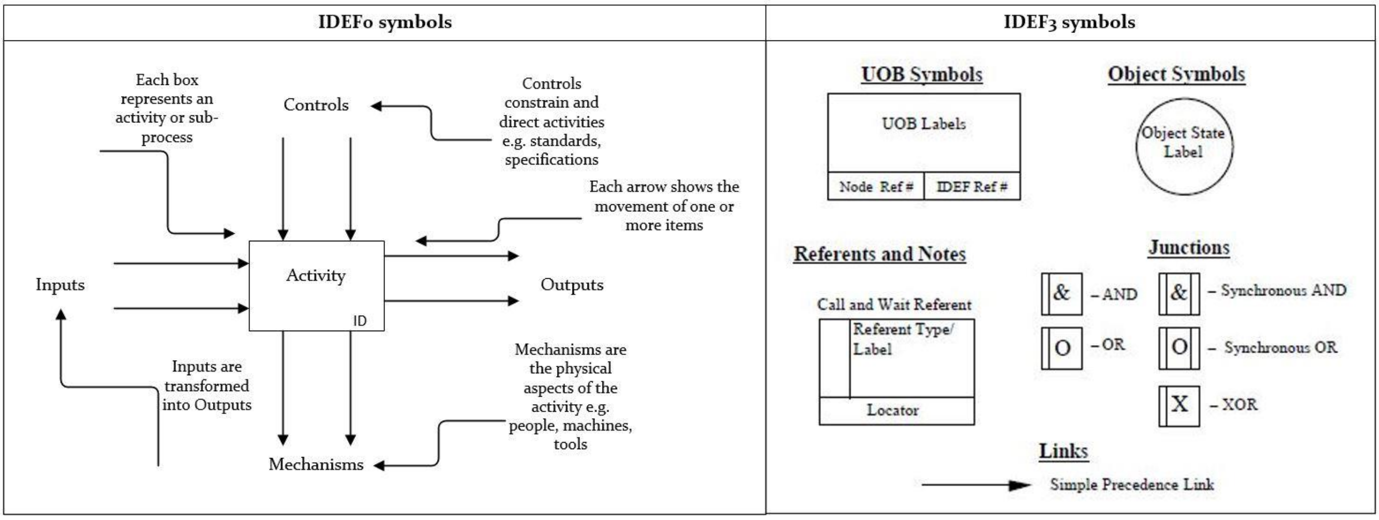


Figure 1 Symbols used for process description schematics

Overview of process decomposition

The process model aligns with RIBA's (2013)[3] stages 0 (Strategic Definition), 1 (Preparation and Brief), and to 2 (Concept Design). These stages correspond to the three stages of briefing; Strategic, Initial, and Final, respectively. Figure 2 presents the IDEF model's master-map, which consists of three level hierarchies. Level 1 represents the high-level IDEF0 process model decomposition aligning with the RIBA's (2013) hard decision gates, and colour-coded accordingly. Level 2 contains the decompositions (sub-processes) of the Level 1 process. Level 3 contains the decompositions of the Level 2 processes. Levels 2 and 3 (IDEF3) provide granularity that demonstrates which functions are performed by each role, parallel activities, and soft-gates. Table 1 contains the three levels of IDEF decomposition diagrams and Table 2 the critical decision points (IDEF3 model Junctions), aligned with sustainability criteria for Concept Design (stage 2). The diagrams provide the illustration of the relationships between BIM-enabled sustainability uses (Units of Behaviour, UOB), the gateways and critical decision points (Junctions), and the iterations cycles of the collaborative process. The inputs (information required) and outputs (information shared) of the functions are illustrated as Objects. The Objects' states (e.g. Initial, Optimised, Approved, Shared) change as they are altered by the functions.

[1] Knowledge Based Systems Inc. (KBSI). (1993). *INTEGRATION DEFINITION FOR FUNCTION MODELING (IDEF0)*. Retrieved from http://www.idef.com/pdf/idef0.pdf

[2] Mayer, R. J., Menzel, C. P., Painter, M. K., Dewitte, P. S., Blinn, T., & Perakath, B. (1995). *Information integration for concurrent engineering (IICE) IDEF3 process description capture method report*. DTIC Document. Retrieved from http://www.enterprise-architecture.info/Images/Documents/Idef3.pdf

[3] RIBA. (2013). RIBA Plan of Work 2013. Retrieved from http://www.ribaplanofwork.com/

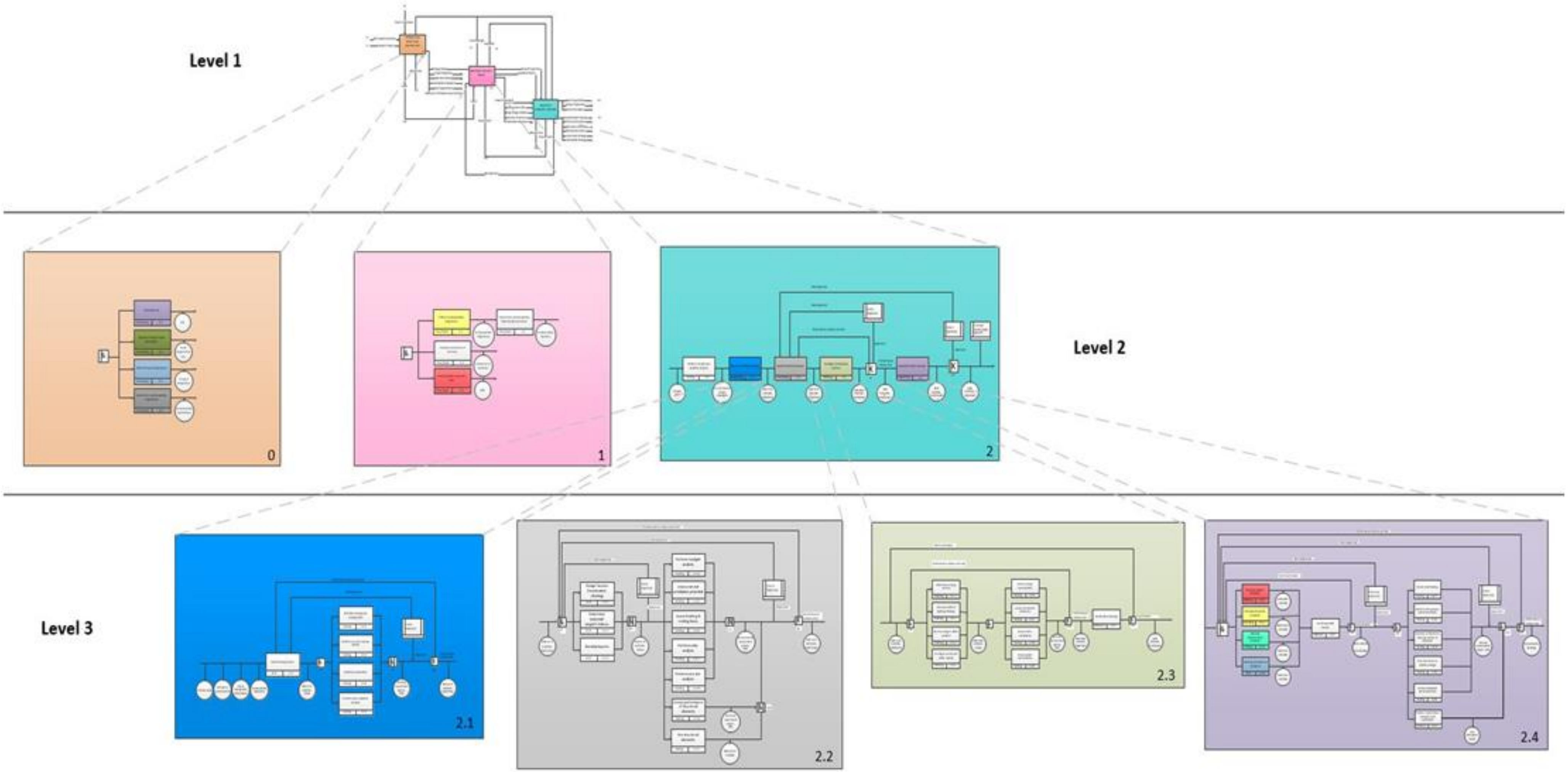
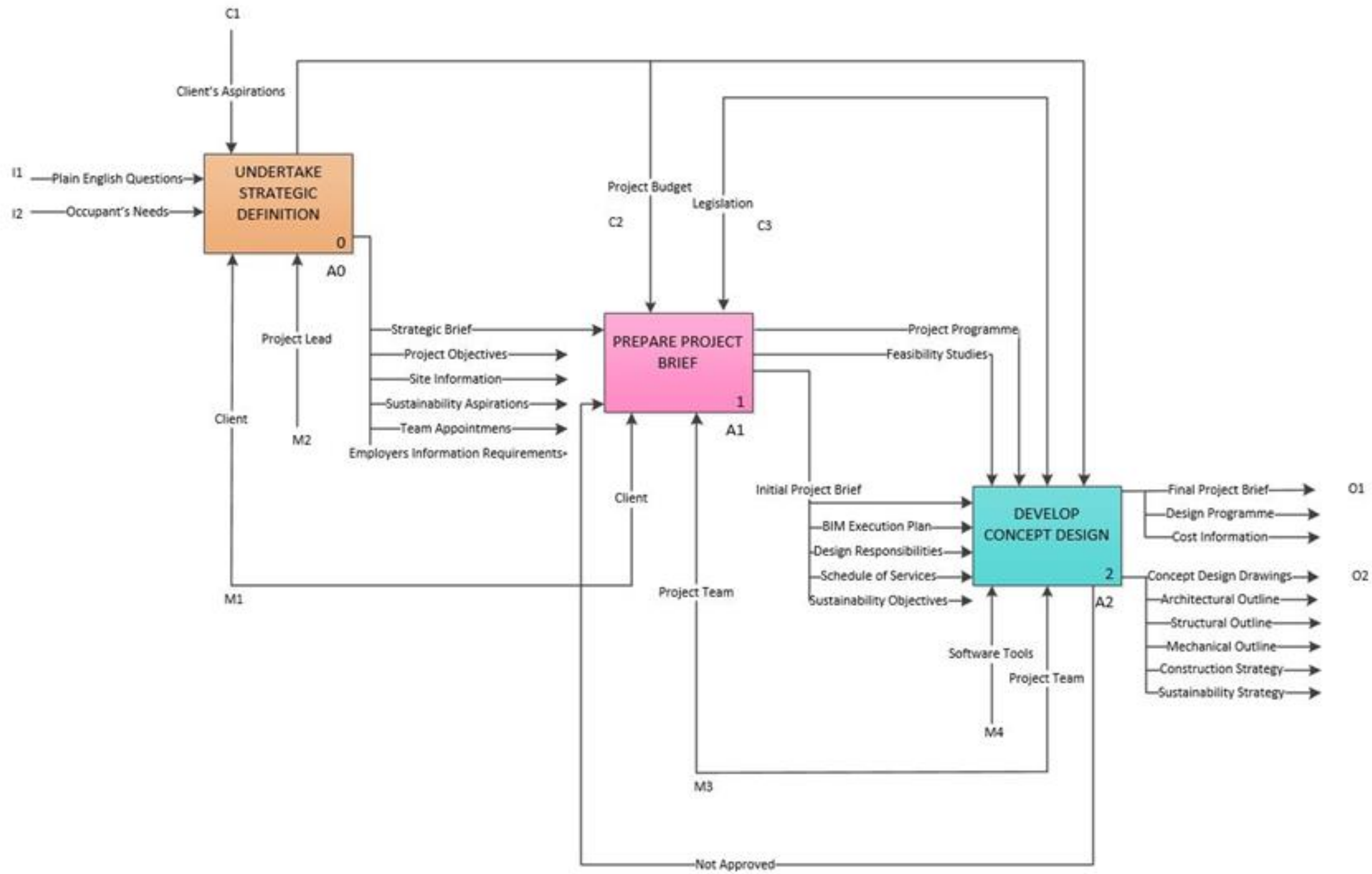


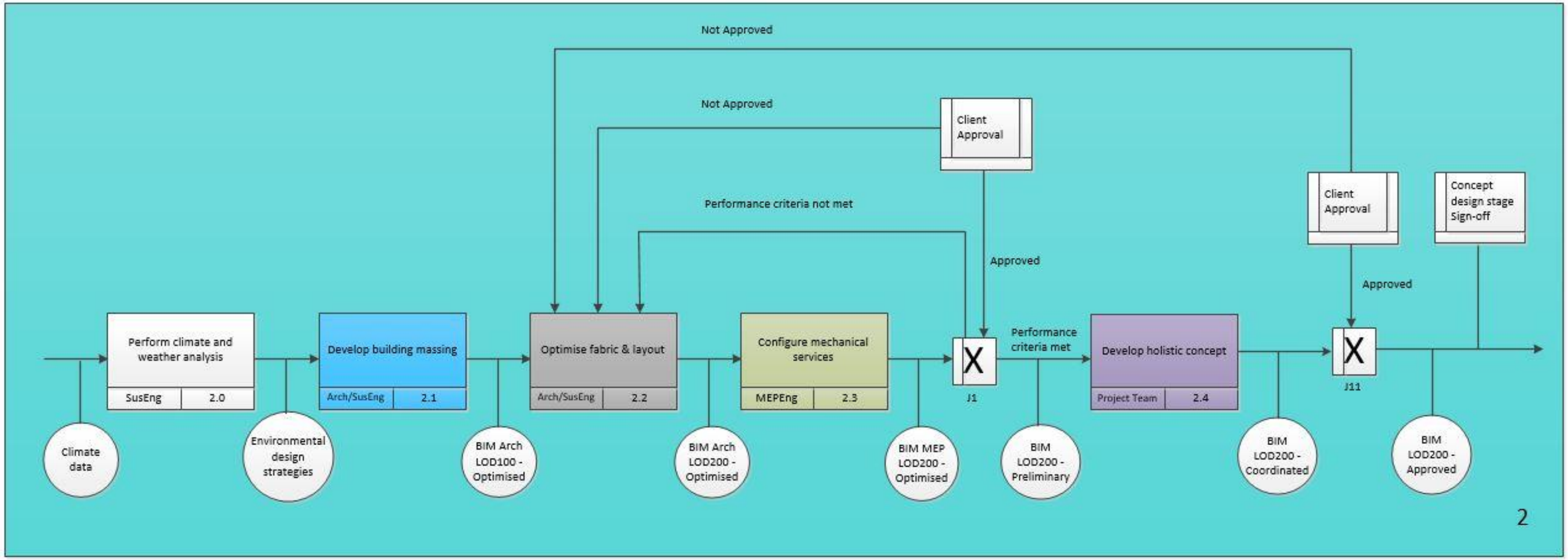
Figure 2 IDEF process model master-map showing hierarchical relationships between processes and their sub-processes (see Table 1 for detailed decompositions)

Table 1 IDEF decomposition diagrams

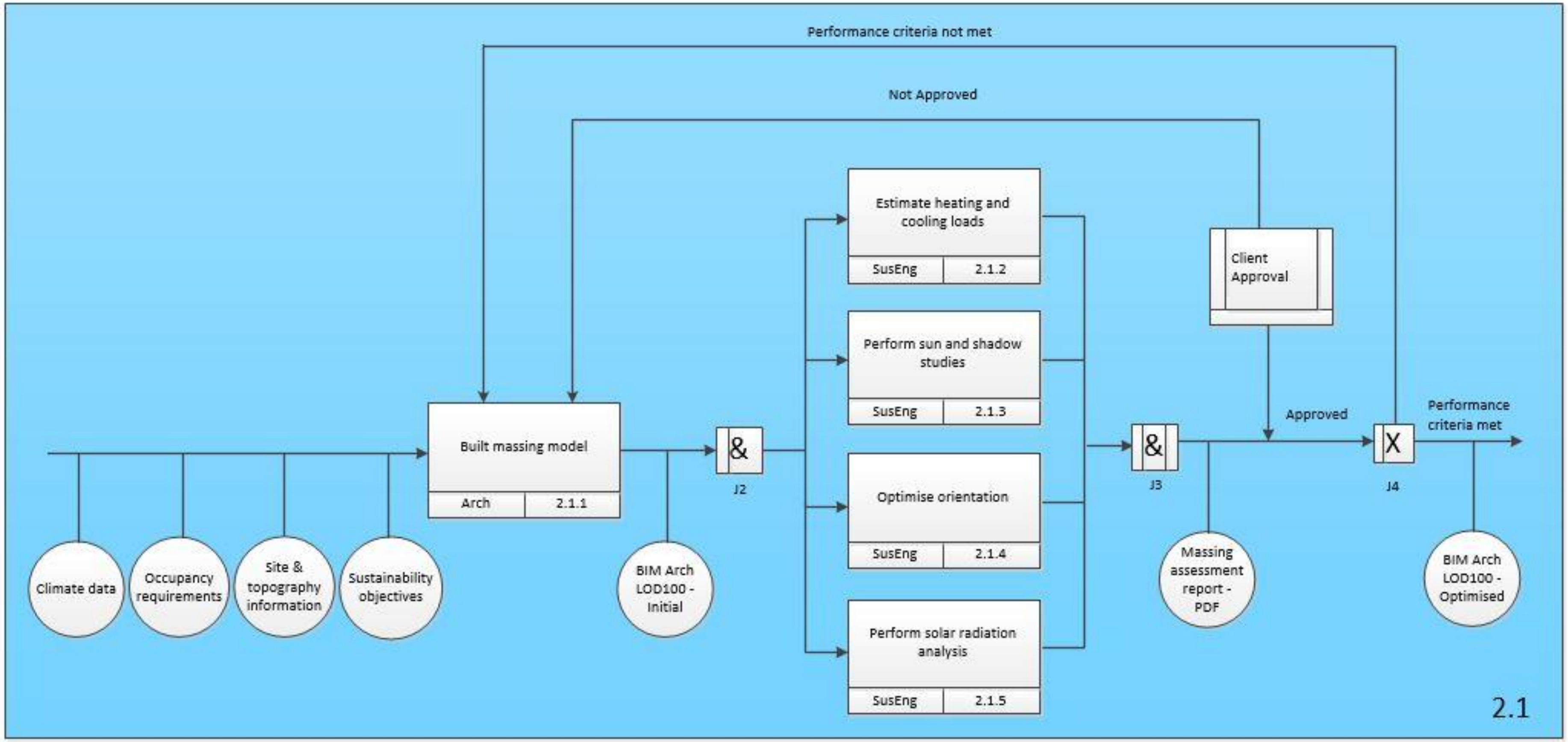
Hierarchical Level 1



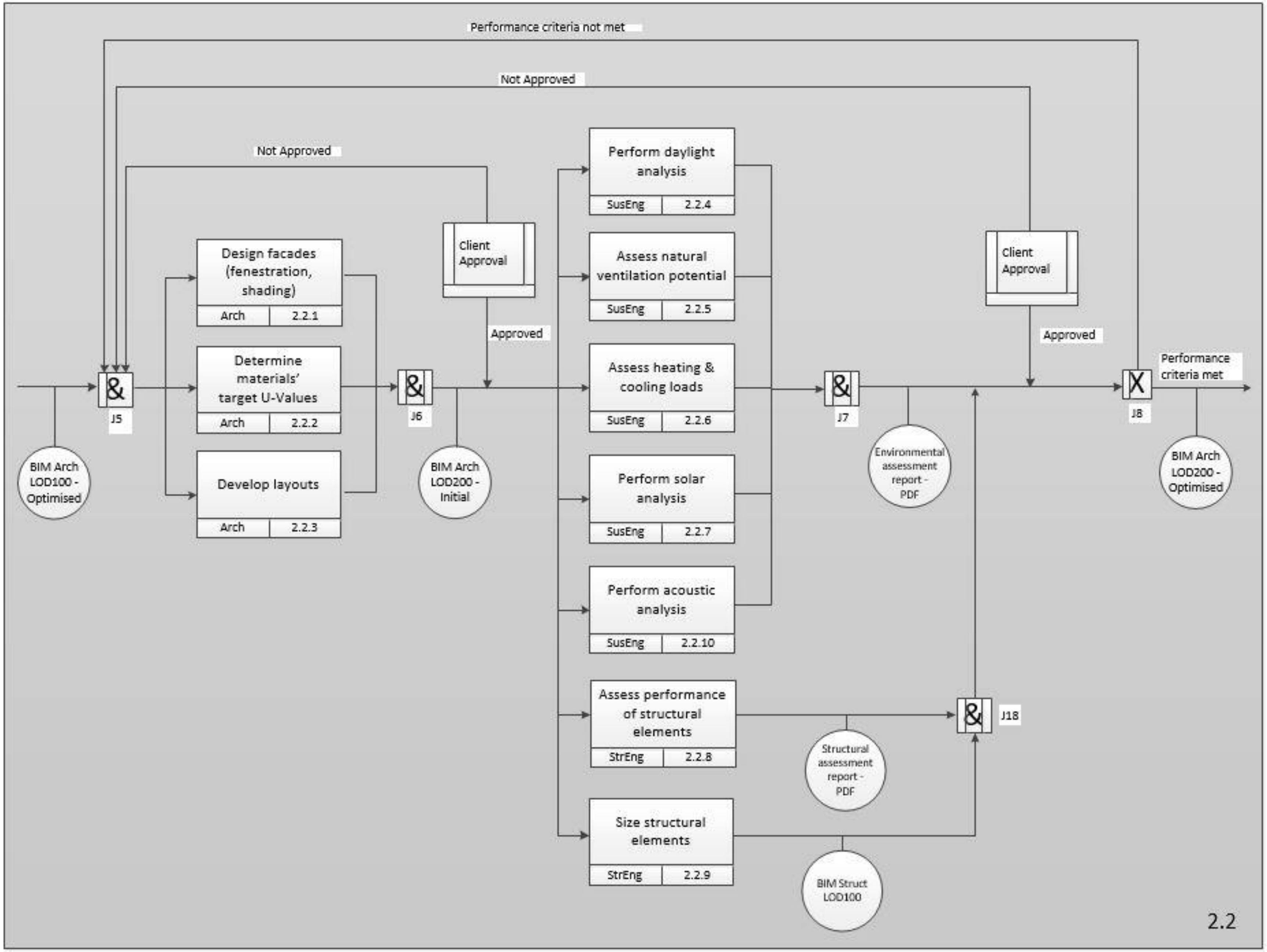
Hierarchical Level 2



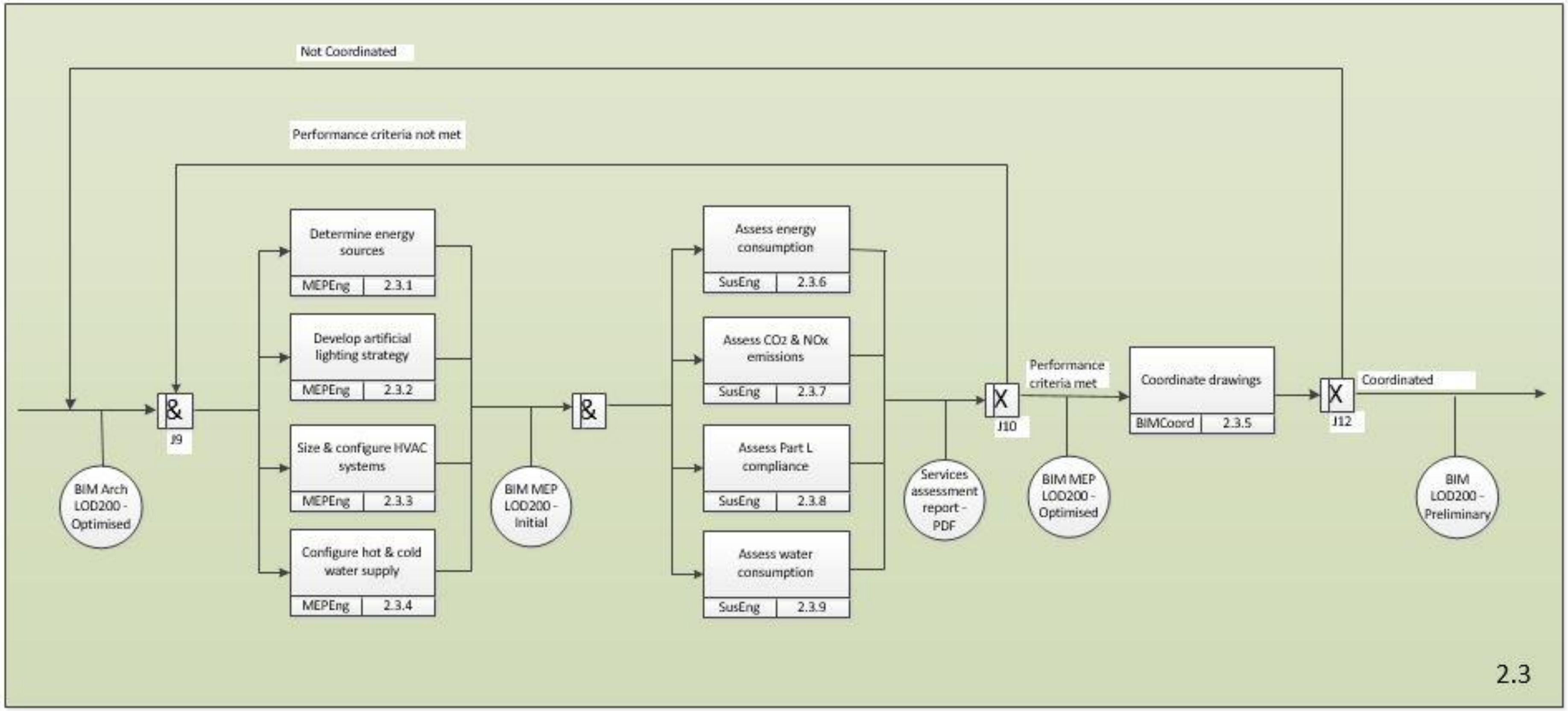
Hierarchical Level 3



Hierarchical Level 3



Hierarchical Level 3



Hierarchical Level 3

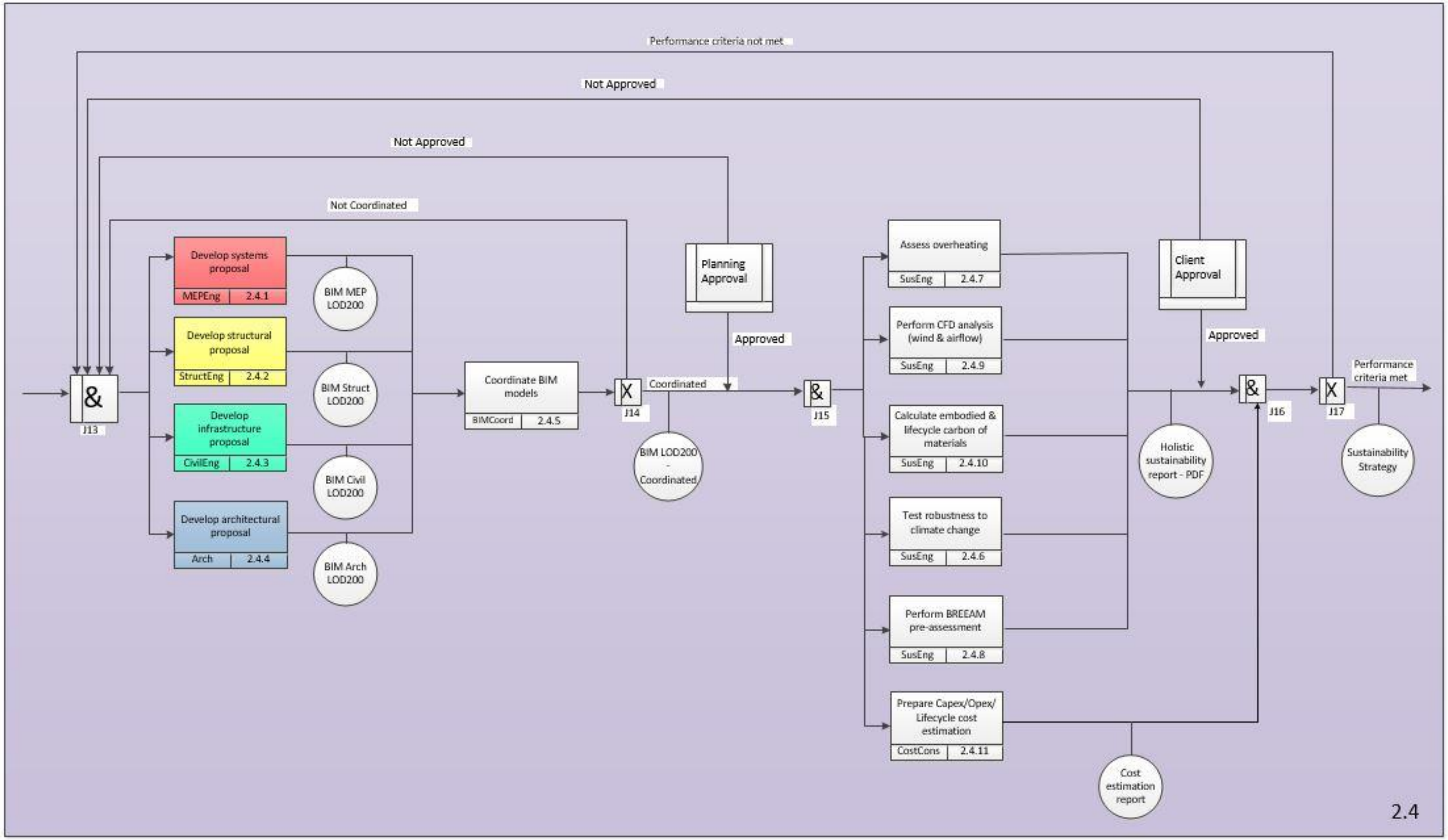
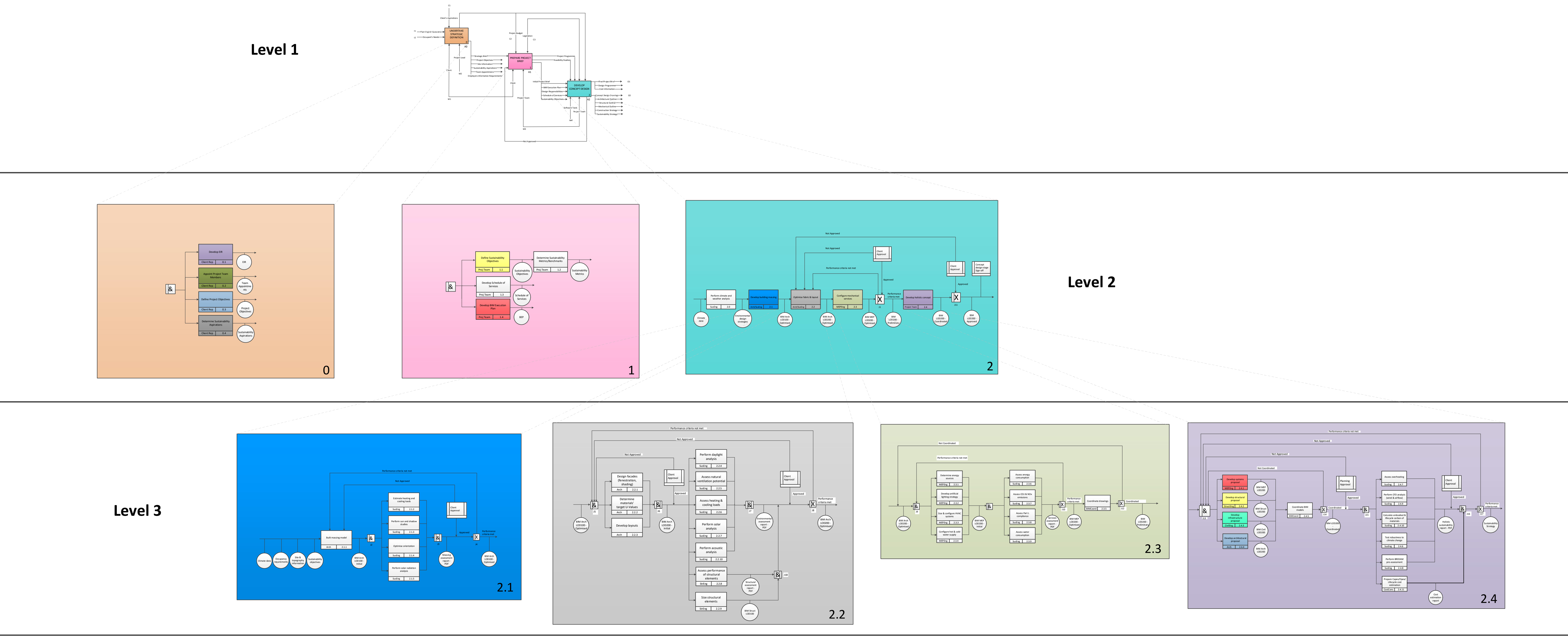


Table 2 Critical decision points (IDEF3 model Junctions) aligned with sustainability criteria

Decision points	Sustainability criteria
Junction J4	4.1. Overshadowing
	4.2. Building height
Junction J8	8.1. Embodied carbon of materials
	8.2. Toxicity of materials
	8.3. Recycled materials
	8.4. Glazing and shading
	8.5. Daylighting
	8.6. Insulation (U-Values, W/m^2K)
	8.6.1. Wall
	8.6.2. Window
	8.6.3. Roof
	8.6.4. Ground floor
	8.7. Airtightness (at 50Pa)
	8.8. Ventilation and cooling
	8.9. Overheating
	8.10 Acoustic performance
Junction J10	10.1. Energy consumption
	10.1.1. Heating and hot water
	10.1.2. Electrical load
	10.1.3. IT and small power
	10.2. Carbon/CO_2 emissions
	10.3. Display Energy Certificate (DEC)
	10.2. Energy consumption
	10.3. Energy source
	10.4. Artificial lighting
	10.5. Water consumption
Junction 17	17.1. Controls and metering
	17.2. IT strategy
	17.3. Capital cost
	17.4. Lifecycle cost
	17.5. Occupancy and user involvement
	17.6. BREEAM rating
	17. 7 Energy Performance Certificate (EPC) score
	17.8 Robustness to climate change



Level 1
Level 2
Level 3
0
1
2
2.1
2.2
2.3
2.4

Questionnaire Handout

Name:
Organisation:

1. *Please select your **role/s** in this organisation (select all that apply):*

- ☐ Client/Client Adviser
- ☐ Architect/Lead Designer
- ☐ Landscape Architect/Ecologist
- ☐ MEP Engineer
- ☐ Structural Engineer
- ☐ Civil Engineer
- ☐ Geotechnical Engineer
- ☐ Transport consultant
- ☐ Cost Consultant
- ☐ Contractor
- ☐ Sustainability Lead/Consultant
- ☐ Sustainability Engineer
- ☐ Lighting Engineer
- ☐ Energy Modeller
- ☐ BREEAM/Passivhaus Assessor
- ☐ Acoustician
- ☐ Public Health Consultant
- ☐ BIM Manager/Coordinator
- ☐ Other (specify): ……………………………………

2. *Please select your **educational background** (select all that apply):*

- ☐ Bachelor in (specify): …………………………..
- ☐ Master in (specify): ………………………..
- ☐ Doctorate in (specify): …………………………
- ☐ Other (specify): ……………………………..

<u>Areas of expertise</u> *<u>(select all that apply):</u>*

- ☐ Architecture
- ☐ Engineering
- ☐ Environmental Physics
- ☐ Sustainability
- ☐ Other (specify): ……………………………….

3. *Please state your **professional experience** in sustainable building design (years/months):*

4. *What **skills and competencies** are required to perform your role, now and in the future (5 years)?*

5. *Please state your **experience** (e.g. tools utilised, years/months) with **Building Information Modelling** (BIM):*

Questionnaire Handout

6. *Please state **your attitudes** towards the following statements (by ticking the relevant boxes):*

	Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
The sustainability criteria need to be set before the design commences.					
The sustainability criteria need to be re-examined after the design synthesis and evaluation happens.					
Trial and error iterations of modelling and analysis optimise the sustainable building design outcome.					
A concurrent engineering process can integrate the sustainability criteria and assessment effectively during multidisciplinary collaborative design.					
A standardised approach to multidisciplinary collaborative sustainable building design increases the possibility to achieve sustainability objectives.					
Automation of repeatable processes can accelerate design tasks.					
A dynamic flexible process is needed for the effective management of organisational workflows during sustainable building design.					

Questionnaire Handout

*Please **review** the IDEF process model description (see separate handout) and **comment** on the following:*

7. Do you believe that the model captures the BIM-enabled sustainable building design process adequately? Why?	
8. Would you add or remove any of its activities, deliverables, or milestones? Which ones and why?	
9. Are the categories and their contents expressed in a satisfactory way? What changes would improve understanding?	
10. In what ways can the model be improved?	
11. Do you find such a model useful? Why?	
12. What do you believe are the benefits of a structured process for sustainable building design?	
13. Would you use and/or recommend the use of Green BIM Box in the future? Why?	

*14. Please summarise your views about Green BIM Box workflow management system in the space below. What do you believe are the **capabilities and features** needed in order to facilitate BIM-enabled sustainable building design within a Common Data Environment (CDE)?*

Please enter your contact details (email and phone number) in the box below if you are willing to provide additional information to your responses:

Thank you for your participation

Appendix C

Examples of data analysis

1. <u>Sustainable Building Design (SBD)</u>
    1.1. Scope
        1.1.1. Health and wellbeing
        1.1.2. Environmental impact
    1.2. Targets
        1.2.1. Certifications
    1.3. Goals
        1.3.1. Constraints
    1.4. Criteria
        1.4.1. Assessment methods
    1.5. Design strategies
    1.6. Critical (incidents vs decisions)
        1.6.1. Participants
        1.6.2. Names of objects
        1.6.3. Objective
        1.6.4. Sequencing and structure
        1.6.5. Trade-offs
        1.6.6. Constraints
        1.6.7. Conditions that hold during the process
        1.6.8. Conditions that are signal the termination of the process
        1.6.9. Processes triggered
        1.6.10. Properties of objects
        1.6.11. Inputs
        1.6.12. Outputs
        1.6.13. Example
        1.6.14. Lessons learned
        1.6.15. Association of activities with objects
        1.6.16. Source material/information artefacts

2. <u>Multidisciplinary Design Project Management (MDPM)</u>
    2.1. Business case planning
        2.1.1. Constraints
        2.1.2. Legal/regulatory issue
        2.1.3. BIM execution planning
    2.2. Organisational maturity
        2.2.1. Strategic planning
            2.2.1.1. Attitudes
        2.2.2. Risk management/preliminary building performance analysis
        2.2.3. Functions/tasks
        2.2.4. Interdependencies of functions
    2.3. Design phases
        2.3.1. Gateways
        2.3.2. Processing time
        2.3.3. Iteration cycles
    2.4. Communication strategy
        2.4.1. Communication method
        2.4.2. Location
        2.4.3. Network
        2.4.4. Events
        2.4.5. Scheduling

3. <u>Sustainable Design Implementation and Delivery (SDID)</u>
    3.1. Participant selection
        3.1.1. Roles (organisation vs actor)
        3.1.2. Responsibilities
        3.1.3. Actions
        3.1.4. Competencies
        3.1.5. Synergies
        3.1.6. Engagement
    3.2. Deliverables/ design artefacts and components
        3.2.1. Data
        3.2.2. Format
        3.2.3. Level of Detail (LOD)/elements
        3.2.4. Level of Information (LOI)/ analysis
    3.3. Technology
        3.3.1. Software tools
        3.3.2. Interoperability
        3.3.3. Common Data Environment
        3.3.4. Capabilities
        3.3.5. Limitations
        3.3.6. Selection criteria
    3.4. BIM maturity
    3.5. Examples

Count	Identifier	Duration (minutes)
1st set of data collection (Phase 1: Exploratory)		
1	R1/I01/ARCH/SD	60
2	R1/I02/ARCH/SC	60
3	R1/I03/ARCH/SD	60
4	R1/I04/ARCH/SC/BM	90
5	R1/I05/ARCH	60
2nd set of data collection (Phase 2: Main Data Collection)		
6	R2/I01/ARCH/SC	60
7	R2/I02/ARCH/SC	90
8	R2/I03/ARCH	50
9	R2/I04/ARCH/SC	50
10	R2/I05/PRM	30
11	R2/I06/BC	60
3rd set of data collection (Phase 2: Main Data Collection)		
12	R3/I01/BM/BC	55
13	R3/I02/BA/SC	30
14	R3/I03/EE/SD/BA	53
15	R3/I04/ARCH	61
16	R3/I05/SC/BA	50
17	R3/I06/SD/SC	35
18	R3/I07/SE/SC/BA	71
19	R3/I08/SE/BA	40
20	R3/I09/SE/BA	45
21	R3/I10/ME/SD/BA	33
22	R3/I11/SE/SC	32
23	R3/I12/ARCH/SC	50
24	R3/I13/SC	70
25	R3/I14/ARCH	47

KEY	
ARCH	Architect
PRM	Project Manager
BC	BIM Coordinator
BM	BIM Manager
BA	BREEAM Assessor
EE	Environmental Engineer
SC	Sustainability Consultant
SD	Sustainability Director
SE	Sustainability Engineer
ME	Mechanical Engineer

Interviewee (identifier)	Excerpt from transcript or summary	Coding
R2/I02/ARCH/SC	They receive 2D drawings and they receive the full Revit model 3D. The PHPP report, and they use that to build their own model and the analysis they do... daylighting, overheating, system design (ventilation system heating system, controls design – a little bit.)	design deliverables are a mixture of 2D drawings, and 3D Revit model, PDF analysis reports
R2/I03/ARCH	and I think how, not least how software develops, and also with our understanding of what you can do with the software in terms of organisation, how you handle data in the model from an early stage, it's far easy at the start to put data on day one that it is, trying to retrospect different organise parameters, data and output layout. we are continuously working towards that goal now of trying of having standard templates and standard ways of working, means that always we are trying to improve compatibility, not least saving a lot of time. Just think of the amount of time that is being spend by the services engineers to fire engineers, acoustic engineers in creating their own models essentially. They were creating their own models from our 2D outputs. There is a lot of time and resources taken up there which can only add to the efficiency of the design team and take the required efficiencies and savings back to the client to... one of the main aims of BIM really from a designer point of view. yeah... and beyond that is the construction phase they [name of organisation] provided their own implementation and so they look the further strains to how sub-contractors mainly services, lighting, although it was not a continuing collaborative approach we have a regime of issuing models to co-ordinating and collaborating so ... it did work and the key point is ... really meant that we could turn around a lot of work with a certainty that the services and the lighting and everything else would actually work in there which was crucial for us at various points in the contractor and it was a good ... and hopefully a good case study for everybody in collaboration or be it.	BIM execution planning improved compatibility between software and streamlined the collaborative process
R2/I04/ARCH/SC	in terms of how we produce and share information, architecturally it's very straightforward, the first thing we do is that we start to develop our Revit model which is essentially a spatial model at the start of the building where we layout the arrangement of the building, how locate rooms and volumes to those rooms and at the early stage we basically have a very simple massive model of the building with rooms allocated and spatial requirements. We can then start to put performance standards for those spaces in particular using Revit it's got a ... if you were at my office at the moment we would sat within that model select a room area in there and that brings out a little schedule of performance requirements for that room so for example, if you had known you have like a room data sheet which would describe kind of what the room has to do, so if I say, it needs to be naturally ventilated, temperature somewhere in between 18-28 degrees, a range of temperature that you have to achieve, the room would have 3 people occupying it or if it is an office it will have 30 people, or if it is a standard classroom, all of that criteria can be put into our model essentially as a schedule of rooms tighten in to the actual model content. we then share that model with the rest of the design team and when the M&E engineer would be looking at performance can go around and select the rooms and understand what they are asked for in terms of the brief and that all comes out or furthering the client's brief. And then, they kind of put the performance of BREEAM that we look for on top of that so that gives you a room by room break down of	Provides a description of a more streamlined process utilising the BIM model as a means of information exchange for sustainability information

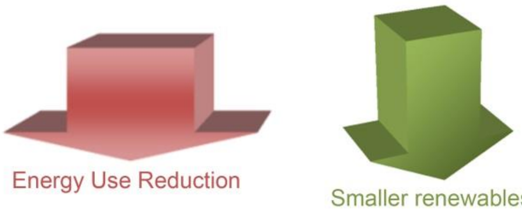
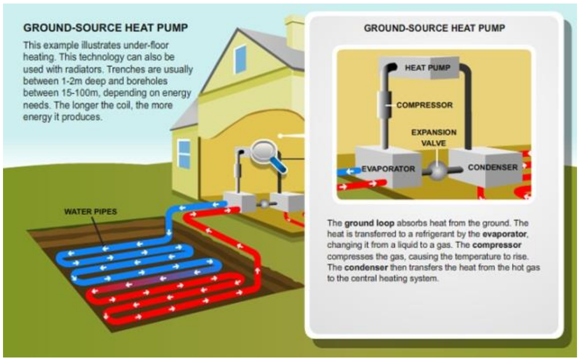
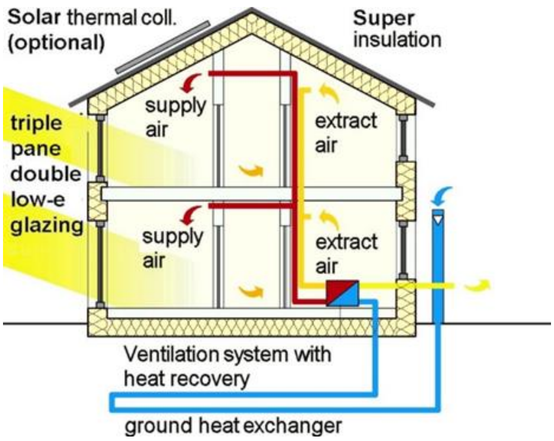
	that information. we then kind of ... we are sharing that information with the design team, it is quite simple because they can all read the software and share the software, so when we share it with the client we present it differently. So, we push that information out.	
R2/I06/BC	Generally the way we work, we are going by a floor by floor basis, basement and overlay the architectural model, the structural model and the building services model. One of the main issues is the reluctance of the architect to remove structural elements of a model to make sure that their models look right, they won't move or remove the structural elements from that. So there is a duplication of the structural elements in the model. When the model is co-ordinated the architects remove the structural elements, but until then, they don't. They want their models to look right, but they are still waiting for the structural engineer. What we normally do is overlay the drawings and that highlights the errors/clashes. What architectural and structural elements are not co-ordinated and then then at the building services, watch genuine clashes of the building from services. And then recognise what is actually a clash. A beam going through a wall is not a clash, it's supposed to do that. It's about understanding how a building works and what is genuinely a clash.	When deliverables are not defined properly, the numbers of clashes increases during coordination becoming difficult to manage
R3/I01/BM/BC	It varies, but ideally we share our model, they use our model and work their own elements into it. A structural engineer would only have their elements in and an M&E would have their elements in and then that is put into the model. So usually, they keep their own model internally for reference and they only share specific information with the rest of the project team.	the BIM manager, who is part of the architectural team is responsible for delivering the model in the form that is useful for the sub-contractors to perform their analysis
R3/I02/BA/SC	We usually make sure that the pre-assessment is done at this stage and show what evidence they should be thinking about and how they can incorporate that into detailed design information. We don't take too much evidence from them at that stage unless there is anything to do with consultation or early involvement with people because their design will probably change so many times. So we are waiting for the detailed design specs to see. Sometimes we get a lot of letters of commitment, that sort of thing, which they can do quite early on, because they are committing to it and they can incorporate it. For concept design, we don't receive too much information at that point. It should happen later on.	BREEAM assessment at concept design
R3/I03/EE/SD/BA	If the model is built in a particular way, it can be exported. But the way it needs to be built, it does not recognise how architects work. The package expects them to build one room at a time and put, the furniture, the glass, and then move on to the next room. What they do is work at a global scale, they design the outside of the building at once and then they design the inside separately. So, what they design it does work. How it can be solved is either by changing the workflow if there is enough time allowed for the model to be constructed in that way or it could be solved by improvements in the software that would recognise the building as built.	the model must contain defined deliverables so as to be useful for analysis
R3/I04/ARCH	Our key aim of BIM is 2D drawings. That is the key information for us in order to get built by the guys on site. We pull out of it, in terms of other information, we are pulling area schedules, for both floor areas and we material areas. Beyond that, a lot of the thing that people talk about, cost or material properties are not	2D drawings, taken out of the BIM model, are the main deliverables

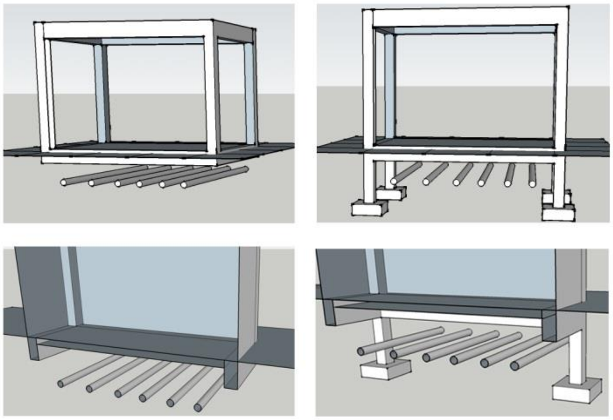
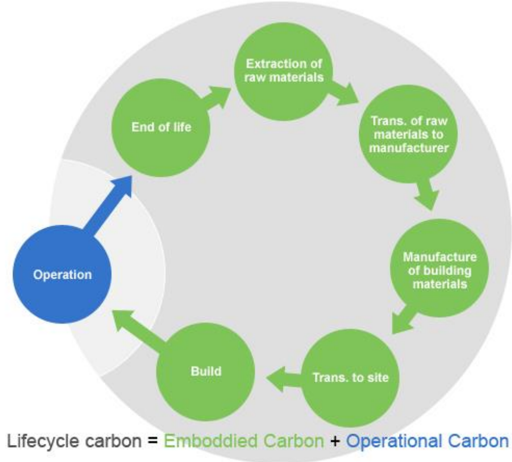
	something that we are putting into it at the moment and the key thing is to take some measurements and the M&E engineers they are utilising it in their own way. If you are talking about things such as the COBie data and how we embed that level of information in, that is not something we are currently doing on the projects. It is going to happen, but we haven't reached that level of development yet.	
R3/I06/SD/SC	There are certain things you use a model for whether it is a BIM model or whether is a separate thing would be debatable. Because a lot of things that you might draw, you can analyse. And if you are looking at something that gives you true representation of the building, there might not be the packages that can analyse that level of complexity and analyse it. So you've got to be careful how you set your model. What you put in a model, you put it to make it look pretty, to meet a specific requirement for a calculation methodology; it could be structural, it could be a daylighting zone, it could be a heating zone or it could be an overheating criteria. So you might need to draw your building differently, depending on you trying to get out of that model. Just so you have a model that shows the building it shows its inside, looking on to it, is good. You could have to have in a space, rooms	the architectural model needs to be developed having the performance analysis in mind from the beginning
R3/I07/SE/SC/BA	I imagine that they start with AutoCAD designs that change constantly, perhaps Revit, if that is possible. We don't utilise that at the moment. The Revit group is constantly up to date with the changes of the architects. But we don't do all the functions within Revit, we use IES or the structural engineers run their programmes. All the members of the design team receive the (architectural) model and they all use different specialised software to run simulations. We always receive a state of the model, not the final one. That fact causes duplicate work and time losses.	sustainability engineers cannot keep up with the architectural design since they don't utilise the same model for performance analysis
R3/I08/SE/BA	We tend to use it (the BIM model) as an information resource, I would say. Projects which are implementing BIM, we use the BIM model/information, we… how much we are feeding I to that is limited. On the building simulation side, we tend to use things like a building model that might be produced in Revit, for instance, and we use that as an information resource so we can examine the model to understand things like geometry or other building information that we need to perform our own simulations. We share BIM models that other people made, Revit is an obvious example. We might try to import building geometry into our own analysis software without having to create models ourselves from scratch but we are very limited in the work that we do this way. It is a work in development at the moment ... the model is a useful resource because it. Having a 3D model with a lot of information within it, as we are constructing models, we can interrogate the Revit model and hopefully find out a lot about the building fabric; for instance things like U-Values, light transmission, G-values for glazing; we can take sections, you know, if the geometry is complex, we can examine that model, we can create our own sections. Elevations, we can really understand the geometry in much more detail. So, when is say Revit models are very good resource, that's what I mean; there is a lot of information embedded in there which without the Revit model, it would be quite difficult to find.	The architectural BIM model is used solely as an information resource. The performance model needs to be developed in IES separately.
R3/I09/SE/BA	(the outputs of the analysis) It's usually in the form of a report type submission or something. If it's a PowerPoint presentation and a report format. You get the information, you get the numbers, It's all numbers of	Due to lack of two-way interoperability the outputs of the analysis are reports. Those

	the analysis. Numerical and you interpret that information and represent it in the report, very short report that summarise the output.	are not integrated in the BIM model.
R3/I10/ME/SD/BA	We still work very heavily in 2D drawings. That is our main deliverable many CAD package whether that's 2D, 3D or true BIM model. We have also looked at producing schedules but that is not really live and running yet. … We also do render the visualizations so the people can see what they can look like. And we do occasionally share the 3D models back with them and occasionally we would do 3D PDFs or only CADs so they people can see if they need to.	2D drawings, taken out of the BIM model, are the main deliverables
R3/I11/SE/SC	I don't find that we use the model for collaborative BIM. The model tends to get when we do our concept design. So, at concept design stage we tend to do sketches, so we will have workshops, we will have sketches, we will have strategies, drawings… all our concept design work is still done by hand. And then once we've got our scheme works, we would then input it into BIM and then it gets updated and it is going forward. But during concept design we would collaborate with the designers, do sketches by hand, mark-up those and move things around. This is just the way that we do it.	2D drawings are the main means of communication for concept design
R3/I12/ARCH/SC	(the BIM model) It's floorplates and internal walls, external walls, not really defined at that stage. We probably wouldn't put it in the model (U-Values and specifications) or we would put it in quite generic information at that stage because so much.... you need another level of design to get to that stage to put all that information in. ... We get a report. It is quite a simple PDF report.	Exampled of a more streamlined process (information contained in the BIM model that is ready for analysis). However, lack of two way interoperability hinders integration of sustainability (the outputs of the performance analysis are reports)
R3/I13/SC/BA	(I receive) geometrical things; the building elements, the volumes, materials (building envelope), and particular sorts of data attached. I am not sure if that counts for BIM though. ... . A range of people form the design team, they are providing evidence as regards to certain criteria; PDF format and what else is defined by BRE; PDF documents, Word documents, and Excel files, standard types of data and emails also.	BREEAM assessment deliverables
R3/I14/ARCH	It was a mixture, certainly with thermal modelling it is allowed you to see snapshots of the model to prove, to saw the issue at hand. A lot of it sometimes, an opening at mechanical engineering space in the area, when you can get X meters of openable area, we would then go and remodel it and use it to determine the fenestration of the building. There is a mixture of spatial requirements, it could be snapshots of the thermal model that you have built, it could be snapshots of our design (e.g. elevational options) of what it meant, what we are trying to do with this. We might had to communicate the people providing the windows to see what we can and cannot achieve. ... Because fundamentally, you still need to come up with a concept, and a design whether you do it in 2D or 3D or if you do had drawings; fundamentally that will be the same.	Snapshots from the BIM model and BPA model included in the reports delivered. Argues that the process does not differ whichever the deliverables.

Preliminary analysis of incidents' workflows (flowcharts)

<u>Incident description: thermal tubes compromise structural integrity</u>

1. The architectural team suggested first to reduce the energy consumption of the building and then to add renewable sources; that would result in smaller renewables. **Participants:** architectural team, MEP engineers	
2. After testing the alternative options (under-floor heating & ground source heat pumps), the cost assessment revealed that the mechanical ventilation with heat recovery combined with an earth-tube was the most effective solution. **Participants:** architectural team and MEP engineers, cost estimator	
3. Initially, the tubes were intended to run in the playground in front of the building of the building but resurfacing the pitch was considered more costly. The supplier of the tubes advised that the putting them underneath the building would not change their performance, so the air tubes were moved in the design. **Participants:** architectural team, MEP engineers, air tube supplier, cost estimator	

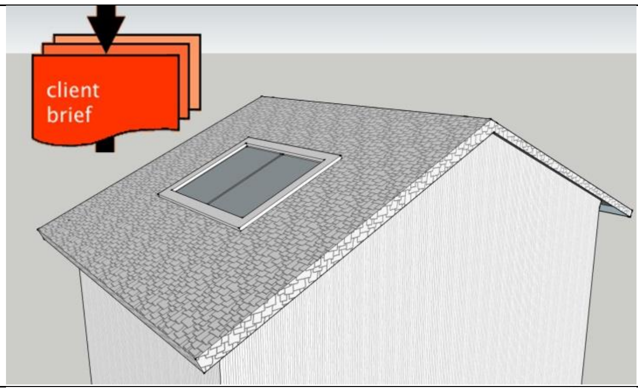
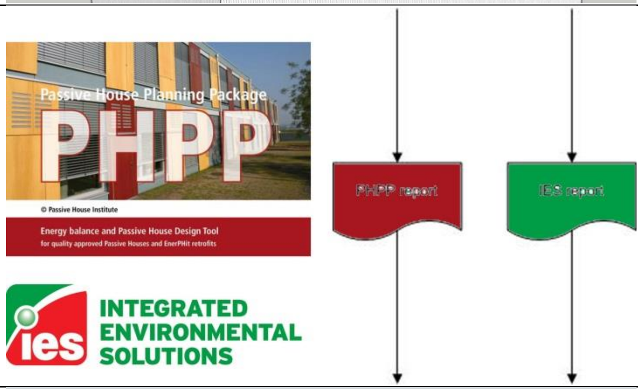
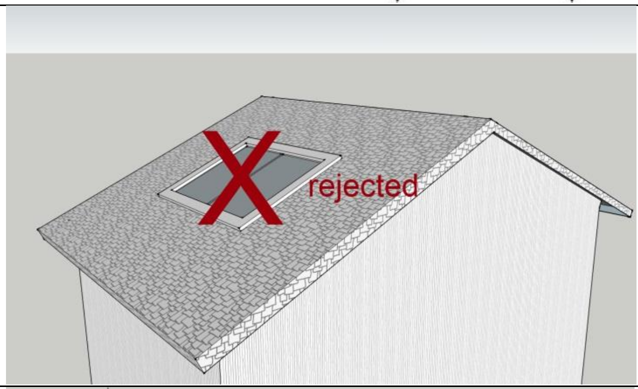
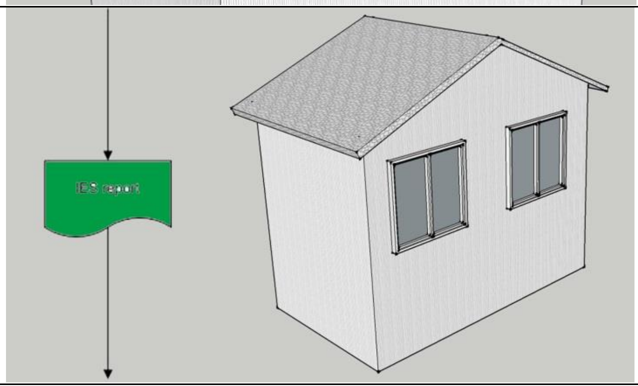
4. The structural engineer was involved at the detailed design stage, and claimed that the compaction on top of the pipes was not safe for the building. Although the team was aware of the problem before the construction phase was reacted, nothing could change at that point since many cost decisions had already been made and there was no time left. **Participants:** architectural team, MEP engineers, cost estimator	
5. The massive concrete foundations that run round the building added a significant amount of embodied carbon to the building. As a result, the carbon savings of the pipes would need 50 to 60 years of building operation to pay off for the embodied carbon of the concrete foundations in the lifecycle carbon calculations.	

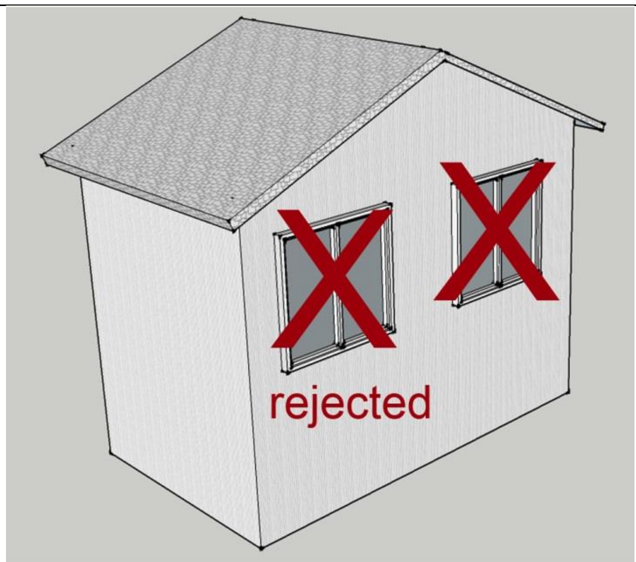
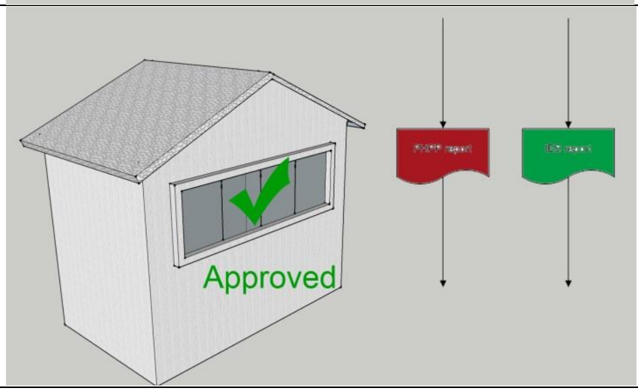
This example revealed that good practice decisions are hindered or even lead to unwanted design outcomes due to lack of coordination among the design team. As in the majority of building projects, time and budget are the main constraints within the design teams have to work. In this case, poor management and the late involvement of the structural engineer has significantly affected the sustainable outcome of the project. As the interviewee revealed:

"It wasn't an analysis issue, the analysis was all done and it was a pretty obvious decision to make if we would just know… if we had been aware earlier that would be impacts with the foundations… we needed the structural engineer there as well to be able to pick up on this problem, the MEP engineers, the structural engineer and the supplier of the tubes, the architects,; that would have been helpful. Having people there at the right time..."

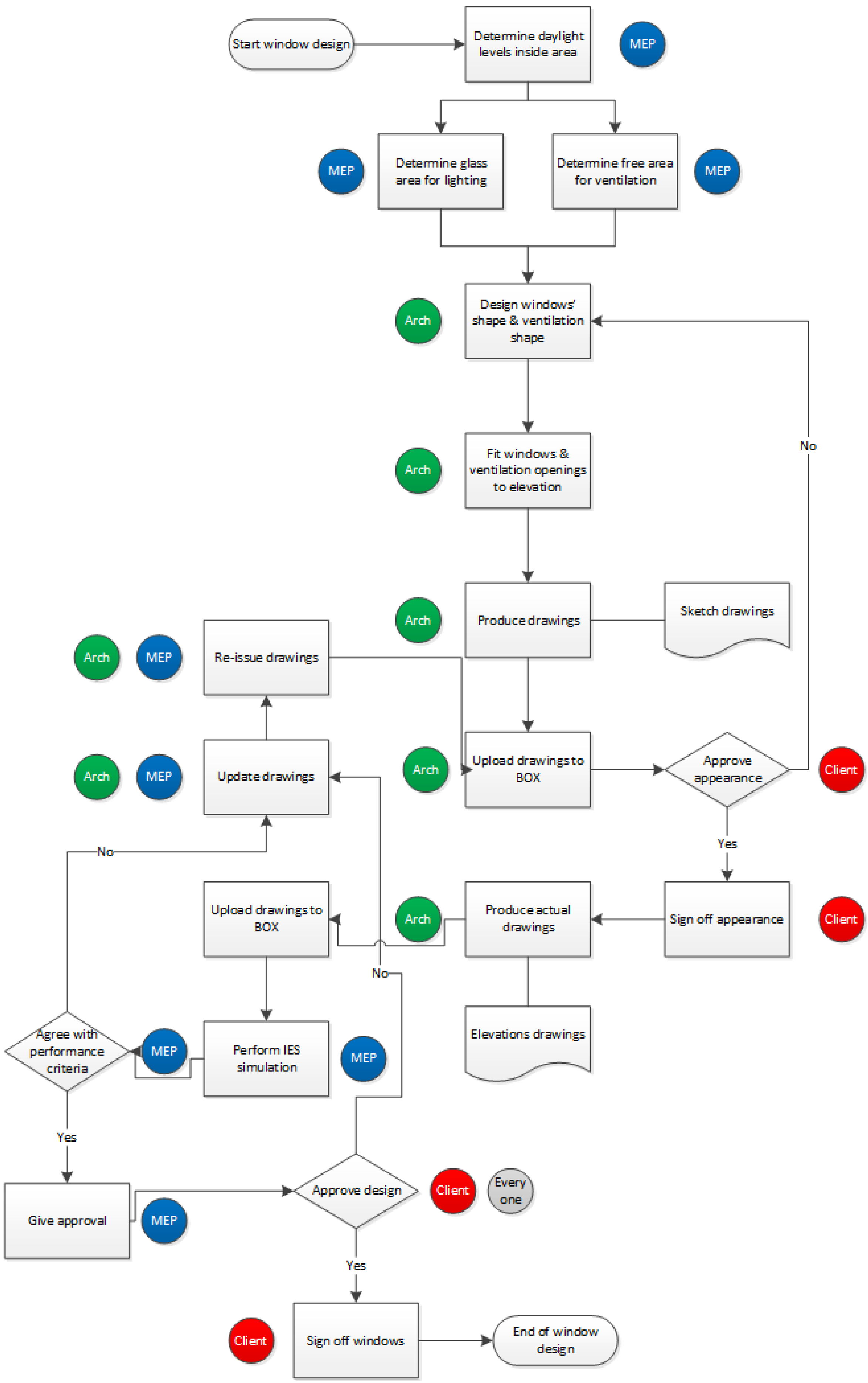
This incident shows that management of the process is vital for SBD. The interrelationships among the allocated tasks need to be clarified from the beginning and that review and updating of the process needs to be happening in a more frequent fashion instead of reviews at key design milestones like the RIBA Plan of Work suggests. No design change should be considered minor; the involvement or all team members is critical to be able to predict those unwanted knock on effects that follow every design decision. A more proactive approach should be employed in the design process and the best cross-discipline design solution needs to be selected as the way forward. An informed BIM model would reveal design conflicts early on in the process and would result in fewer surprises at a later stage when the key decisions are made and there are not enough resources to make significant changes.

Incident description: roof lights requirement causes overheating

1. The architects received the client's brief. Among the other requirements, there is the request of having roof lights.	
2. The architects performed thermal and solar analysis in PHPP and in the meantime the M&E engineers, who simulated the daylight performance of the roof lights in IES software.	
3. The roof lights were found to be an inadequate solution due to them causing overheating during the summer. The architects suggested that they should be removed from the design.	
4. Then, the architects asked again for the advice of the MEP engineers regarding the glass area required for daylighting and the free area for ventilation and then designed the windows' geometry according to those recommendations.	

5. After that, they presented the new elevation design to the client and it was rejected for aesthetic reasons.	
6. This iterative process continued until the adequate balance between daylight, solar, thermal and ventilation requirements was found among the architects and the M&E engineers. The decision was signed off only when each member of the design team approved the result.	

The interviewee described the process as rather linear but highly iterative, until all the design criteria were met. He argued that no decision regarding geometry could be locked until it was analyzed and agreed by the other project participants; iteration and multidisciplinary assessment is the essence of sustainable design. It is apparent that at an organisational level, the breakdown of responsibilities should occur at task level, which is determined by the needs of each project. As the project evolves, so does the process. Despite that fact, there are certain dependencies among tasks that can be defined and modelled. The following graph shows the decision making process of this example and the rules that guided the described incident. The collaboration process in this example appears to be more successful than the previous one; the use of a common data environment has enabled that. The interviewee claimed that the allocation of tasks at regular meetings helped in preventing the duplication of the workload. Although that is true up to a point, as the design is rapidly changing, the same should happen for the process, so as the rest of the design team can be able to keep up with these changes. Despite the fact that the architectural team had built a Revit model from conceptual design stage, the M&E engineers preferred to create their own model in IES. There was no technological barrier in exporting the geometry, schedules and specifications from Revit software to IES, but the team preferred to keep the control of their own model and the exchange of information was the reports and PDF files through the common data environment. The interviewee supported the notion that reason that hindered a more streamlined process, in that case, was not an interoperability issue but the cultural preferences of the MEP team.



Start window design
Determine daylight levels inside area
MEP
Determine glass area for lighting
MEP
Determine free area for ventilation
MEP
Design windows' shape & ventilation shape
Arch
No
Fit windows & ventilation openings to elevation
Arch
Produce drawings
Arch
Sketch drawings
Re-issue drawings
Arch
MEP
Update drawings
Arch
MEP
Upload drawings to BOX
Arch
Approve appearance
Client
Yes
No
Upload drawings to BOX
Arch
Produce actual drawings
Sign off appearance
Client
No
Agree with performance criteria
MEP
Perform IES simulation
MEP
Elevations drawings
Yes
Give approval
MEP
Approve design
Client
Every one
Yes
Client
Sign off windows
End of window design

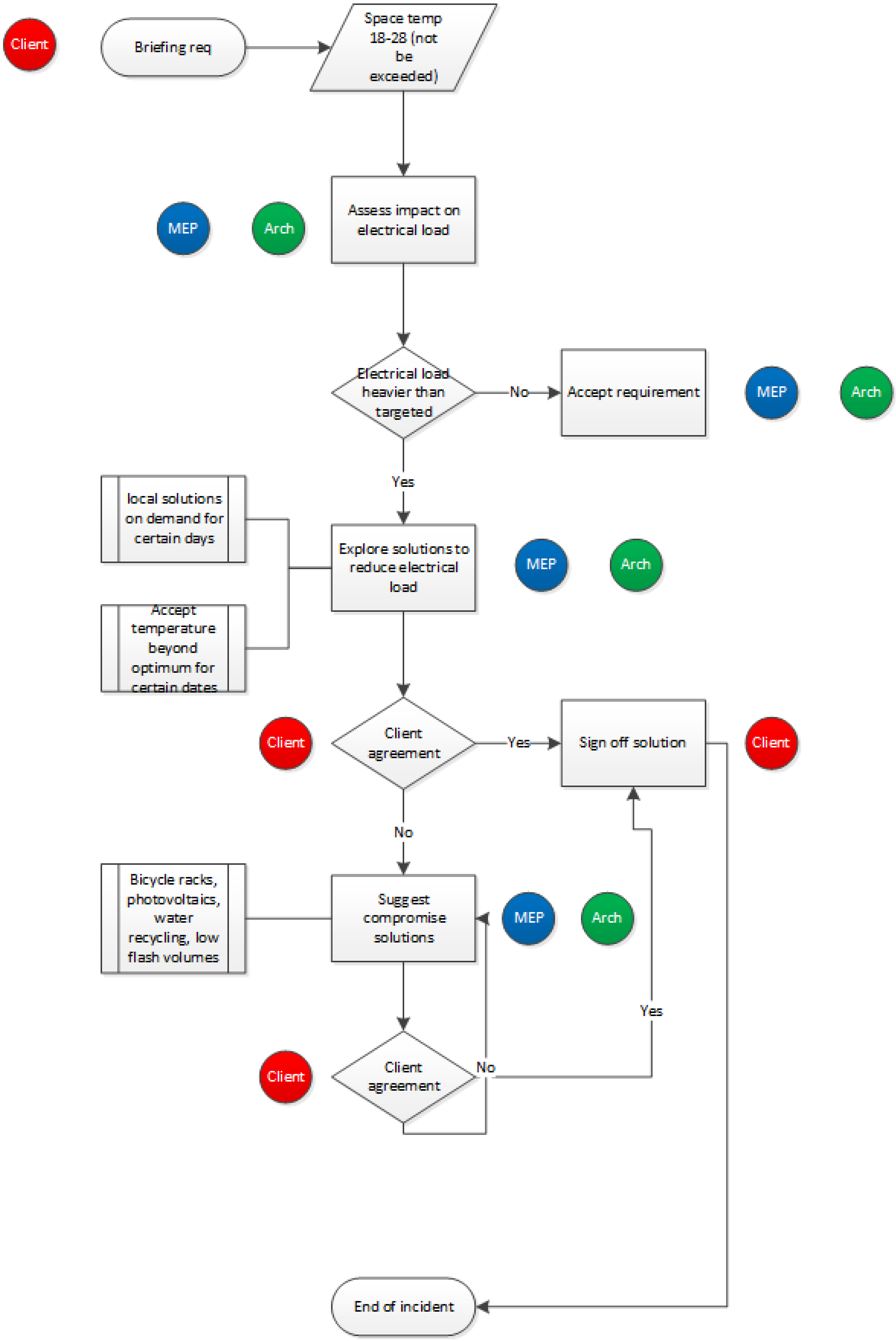
Incident description: temperature range requirement causes increase in energy load

1. Client requests a temperature no minimum than 18 degrees and 28 degrees Celsius pick temperature with the notion not to be exceeded under any circumstances.
2. The architectural and MEP teams tested the alternative options.
3. In order to address the brief's requirement they resulted having huge energy load that lead losing several BREEAM points in the ENE1 section (5 out of 15 credits).
1. In order to achieve the BREEAM Excellent target, they adopted compromise solutions such as water recycling, low flash volumes and bicycle racks.
2. This solution was considered unsatisfactory and was described as "cheating". The building had resulted in poor environmental performance that was the highest priority for the expert.

Learning from that unsatisfactory experience, the interviewee suggested better ways that they deal with in similar situations. The first thing that they do is to model the building (in IES software) 365 days per year to identify the areas that exceed the requirements set. Then, depending on the occupation and use of the space, they consult the client. For example, if it is a personal office, they can accept the temperature to be slightly warmer for a few days per year because the individual has control over the environment and it can be easily adapted. On the other hand, in a lecture theatre they would implement a local solution for cooling in order to restore the thermal comfort when needed. In his own words:

"That analytical full modelling scenario permits us to isolate problems and come up with local solutions for them… analytical modelling at the end stage of design enables to make those critical decisions. If you do it too late in the process, you end up with half-baked solutions, like photovoltaics, to make up for the mistakes. It takes more work upfront and more understanding upfront to be able to do that."

The following flowchart represents the decision making process described by the expert. This process appears to be the most streamlined than the ones described above showing the interactions between disciplines and the gateways where the decisions take place.


Client
Briefing req
Space temp 18-28 (not be exceeded)
MEP
Arch
Assess impact on electrical load
Electrical load heavier than targeted
No
Accept requirement
MEP
Arch
Yes
local solutions on demand for certain days
Accept temperature beyond optimum for certain dates
Explore solutions to reduce electrical load
MEP
Arch
Client
Client agreement
Yes
Sign off solution
Client
No
Bicycle racks, photovoltaics, water recycling, low flash volumes
Suggest compromise solutions
MEP
Arch
Yes
Client
Client agreement
No
End of incident

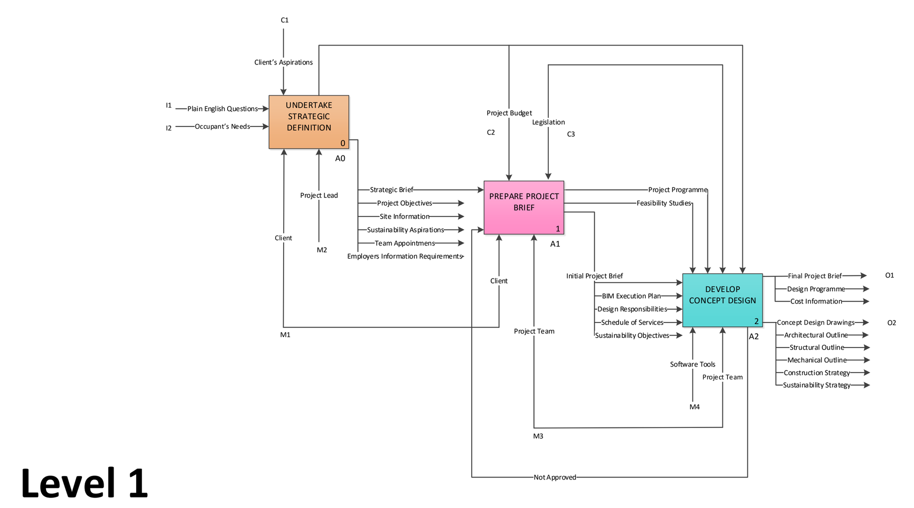
Appendix D

Research outputs

Hierarchical relationships of the model's decomposition Levels

Decompositions (Levels 2-4) are colour-coded according to the higher-level of their corresponding UOBs.

White UOBs are not decomposed any further.



Mock-up's screenshots and database ontology (GBB's Presentation, and Data and Knowledge Access layers)

A. GBB Presentation layer: Mock-up views of the tool's functionalities

Theory development and usability evaluation are directly linked (Carroll, 2000). The development of a UI (User Interface) mock-up is a useful tool for evaluating the human-computer interaction usability of the application. For the purposes of the research, a mock-up of the Presentation layer has been designed utilising Lumzy Prototyping tool[1].

Figure 1 shows the login screen of the prototype application. The user enters their username or email, and password. This window also contains the options to remain logged in, create a new account, and/or a password reminder service.

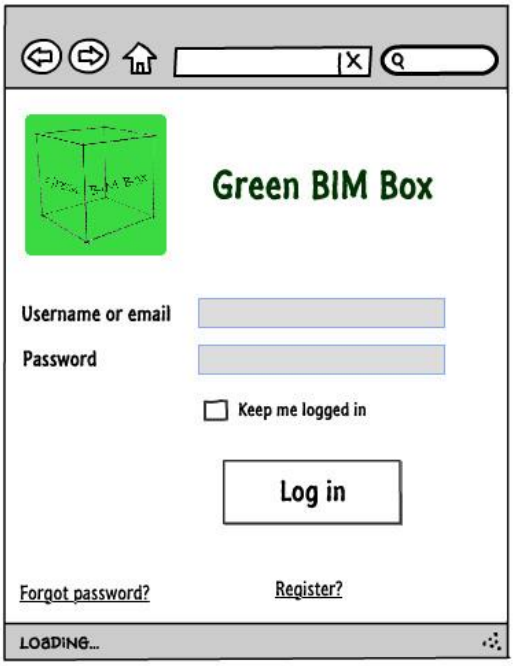


Figure 1 Login screen of prototype application

Figure 2 shows the start-up page of the application. In this window, each member of the project team is able to attain an overview of the project ("*Summary*" tab) as well

[1] http://www.lumzy.com/

as a personalised view of the process ("*My Tasks*" (completed/remaining/ following), "*My Notes*", and "*My Messages*" tabs). These tabs contain their assigned tasks form the Scope of Services, their notes that can be linked with specific Entities (elements of the model or attached files). The "Messages" tab includes asynchronous messages between project members. These messages may include attached files or be linked/tagged to Entities of the BIM model (using Uniclass2015 classification). The "*Notification*" tab includes automatic updates regarding the project's progress (e.g. submissions, or milestones). "*Project Programme tab*" contains critical milestones and dates; its content is presented in Figure 8. Figure 3 presents the link of the "*Overview*" button. This window contains a summary of the project brief; project description, project programme information, project team members, communication means, compliance with regulation and certification schemes. The "*Back*" button (in the bottom right corner) enables the user to return to the Start-up screen. A combo button (top left area of the screen) enables the user to navigate between the RIBA Plan of Work 2013 stages (RIBA, 2013).

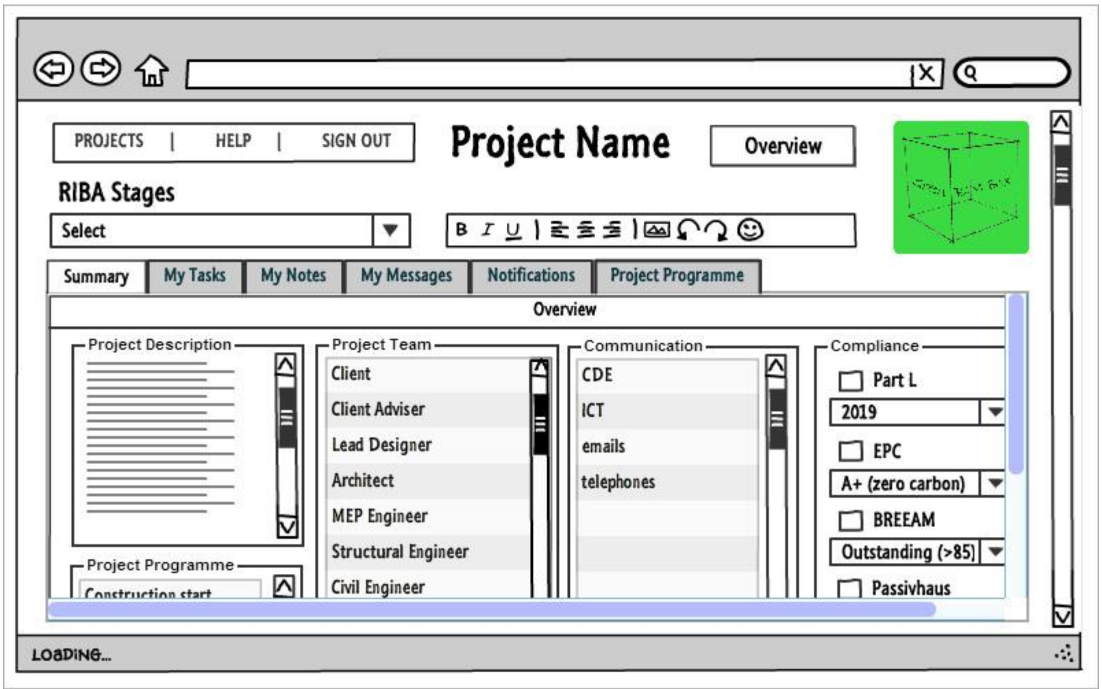


Figure 2 Start-up screen of Green BIM Box (GBB)

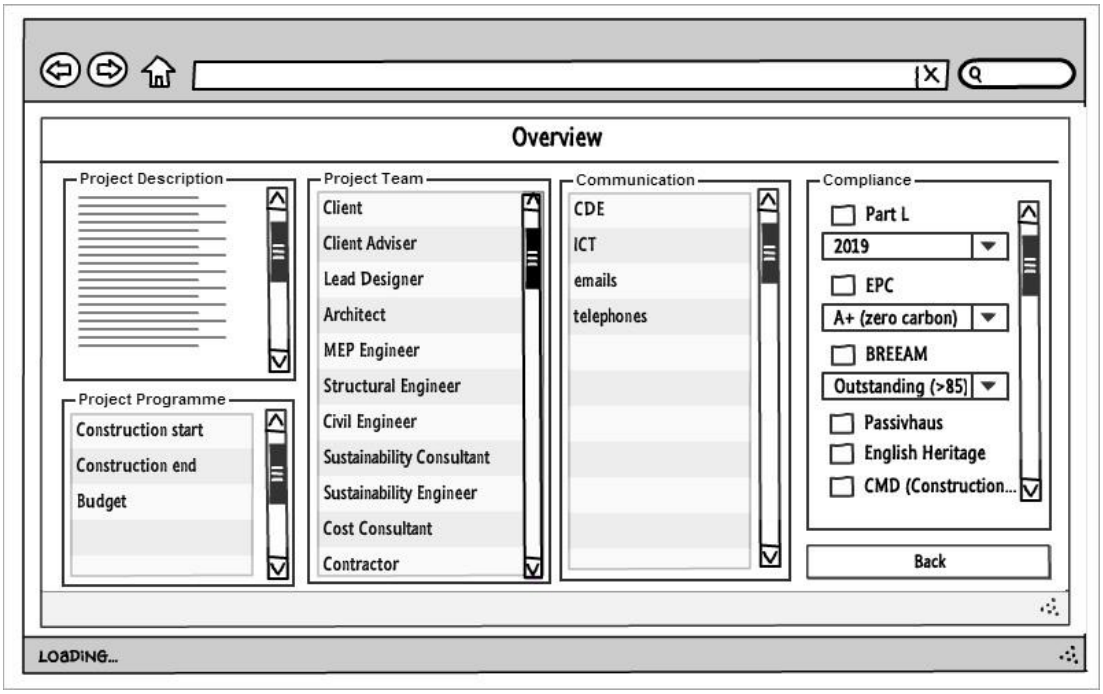


Figure 3 Project Overview screen

Figures 4 to 8 discuss the tabs of Stage 0 "Strategic definition". The first tab "*Employers Information Requirements*" (Figure 4). The second tab "*Project Team"* (Figure 5) presents a list of the organisations name that undertake specific roles for this stage. It should be noted that one role may be shared between more than one organisations, while one organisation may occupy more than one role. Furthermore, this list may change for each stage, based on the requirements of each stage. For this reason, this tab is repeated for Stage 1 "*Preparation and Brief*" and Stage 2 "*Concept Design*". The third tab includes the "*Project Objectives*" (Figure 6), which align with the occupants' needs and requirements for human comfort and health. The project objectives help to identify the scope of the activities that take place in the building so as to address them efficiently through the design. The fourth tab is the "*Sustainability Aspirations*" description (Figure 7). The accordion menu describes the scope of the environmental considerations that occur at Stage 0, as discussed in Chapter 5. The fifth tab "*Project Programme*" (Figure 8) contains the start and end dates for Stage 0, along with the set milestones in list form. The administrator of the process should input these dates. Moreover, based on these milestone dates and the selected tasks on the Schedule of Services, the tool may be able to create a Gantt chart view showing the project's progress (predecessor and successor tasks) (Satzinger et al.,

2010) for four levels of granularity, based on the four levels of the IDEF3 process model. This option makes the process transparent for the design team members who have overview permissions for different levels.

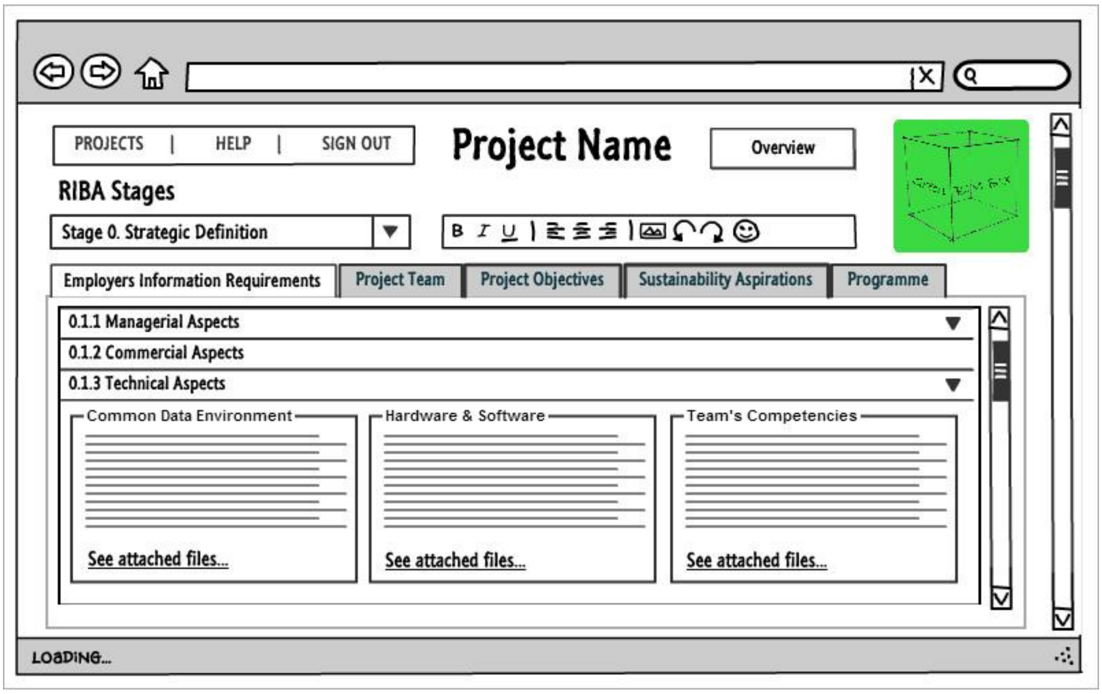


Figure 4 Stage 0 (Strategic Definition) 1st tab - Employers Information Requirements

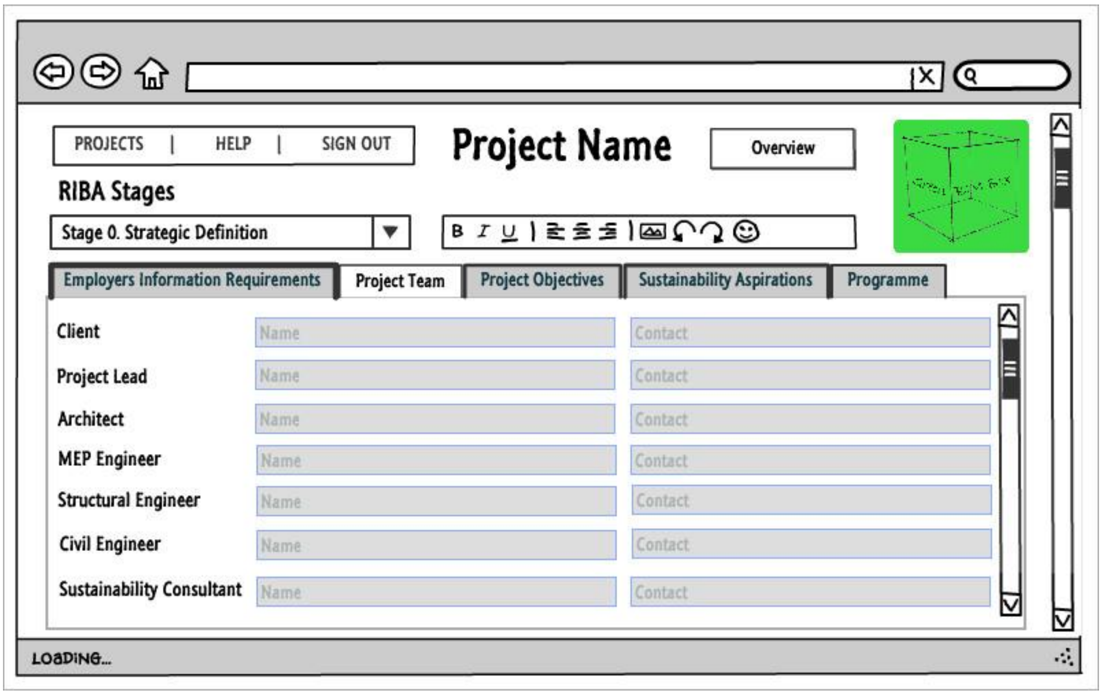


Figure 5 Stage 0 (Strategic Definition) 2nd tab - Project Team

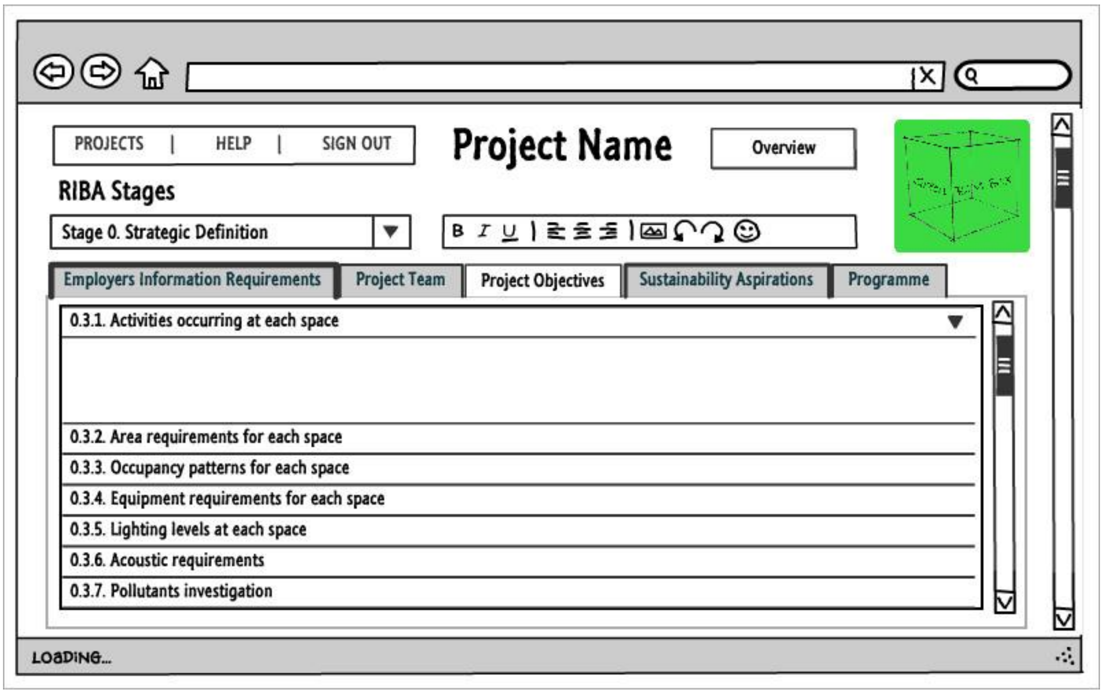


Figure 6 Stage 0 (Strategic Definition) 3rd tab - Project Objectives

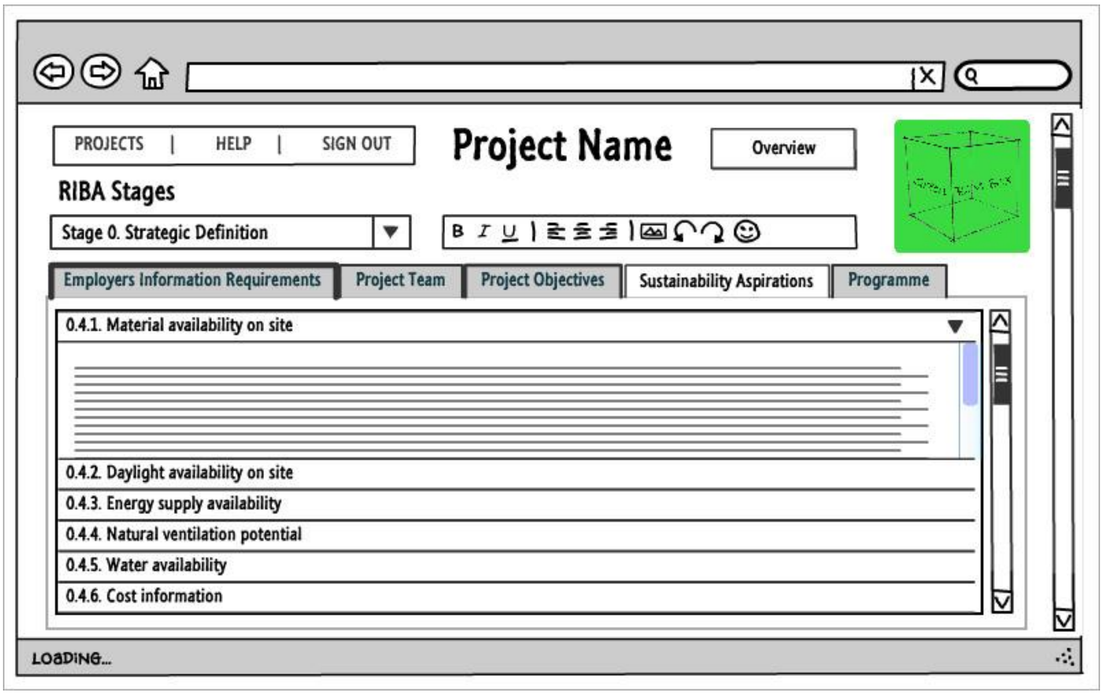


Figure 7 Stage 0 (Strategic Definition) 4th tab - Sustainability Aspirations

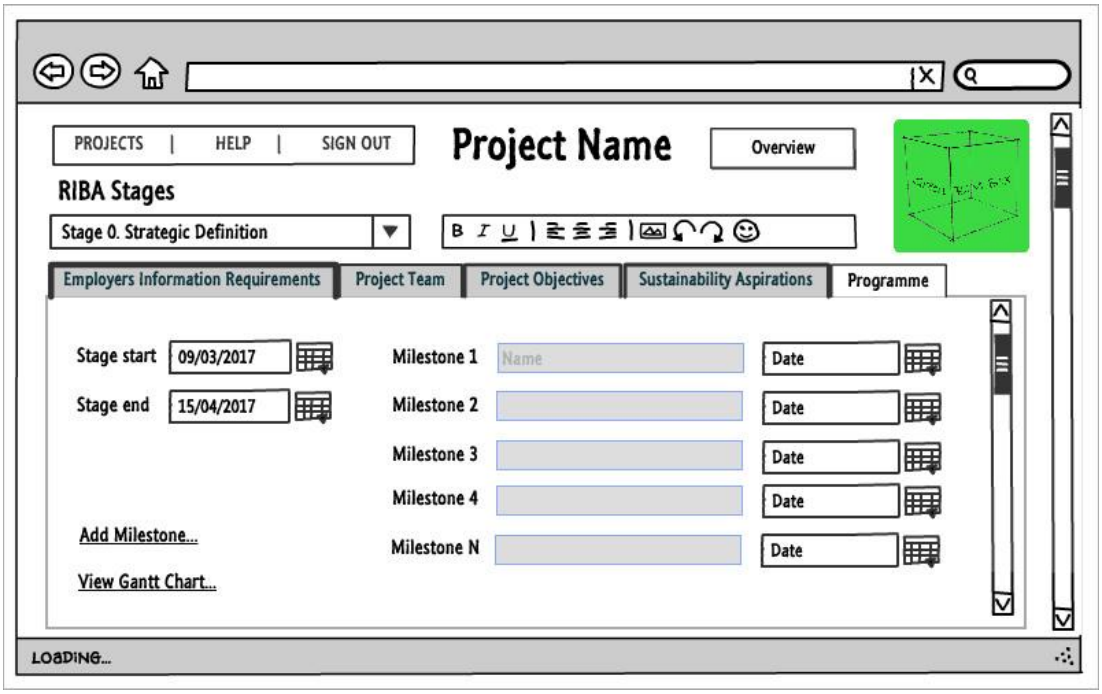


Figure 8 Stage 0 (Strategic Definition) 5th tab - Project Programme

Figures 9 to 15 present the tabs of the RIBA's Stage 1 "Preparation and Brief". The first tab "*BIM Execution Plan*" (Figure 9) provides a summary of the BEP categories discussed in Chapter 6. The second tab "*Sustainability Objectives*" (Figure 10) is divided in the three themes discussed in Chapters 5, 6, and 7 (Fabric, Services, Holistic). Furthermore, the design team is called to select between low, medium, or high design priority. Setting specific measurable objectives and prioritising their importance assists the design team in aligning their design goals and may resolve conflicts that may arise between sustainability objectives. The third tab "*Project team*" is similar as the one described in Figure 5. The forth tab "*Schedule of Services*" (Figure 11) presents the tasks that are selected for each stage, their scope, the responsible party. What is also critical is the fact that the required inputs to perform this task are set. The outputs of each stage are also described for each task. Furthermore, a date for their submission may be set and a count of the submitted version is shown. The inputs and outputs of each may be accessed through links to the database that they reside in the data and knowledge layer of the system. The fifth tab "*Design Responsibility Matrix*" (Figure 12) aligns with the RIBA toolkit's one containing the Classification, Responsibility, LOD, and LOI categories for each deliverable. What is different is that the deliverables status is also updated automatically (awaiting submission, submitted, submitted/awaiting approval, approved, approved/signed-off, rejected, rejected/awaiting revision). File viewing, history, download, edit, or deletion, is possible from this tab. The sixth tab "Project programme" contains the equivalent information as the one presented in Figure 8. The seventh tab "*CAD/BIM Manual*" (Figures 14 and 15) is based on the information discussed in Chapters 3 and 5. This section assists the design team to select the software tools that they will use to satisfy the design goals set (climate and weather, fabric, services, and holistic). Along with selecting the format of their information exchanges, the tool ensures that interoperability issues are discussed and agreed before design commences. What is more, the tool will provide information regarding the interoperability between software tools, providing appropriate selection of choices. The administration of the process may override these settings.

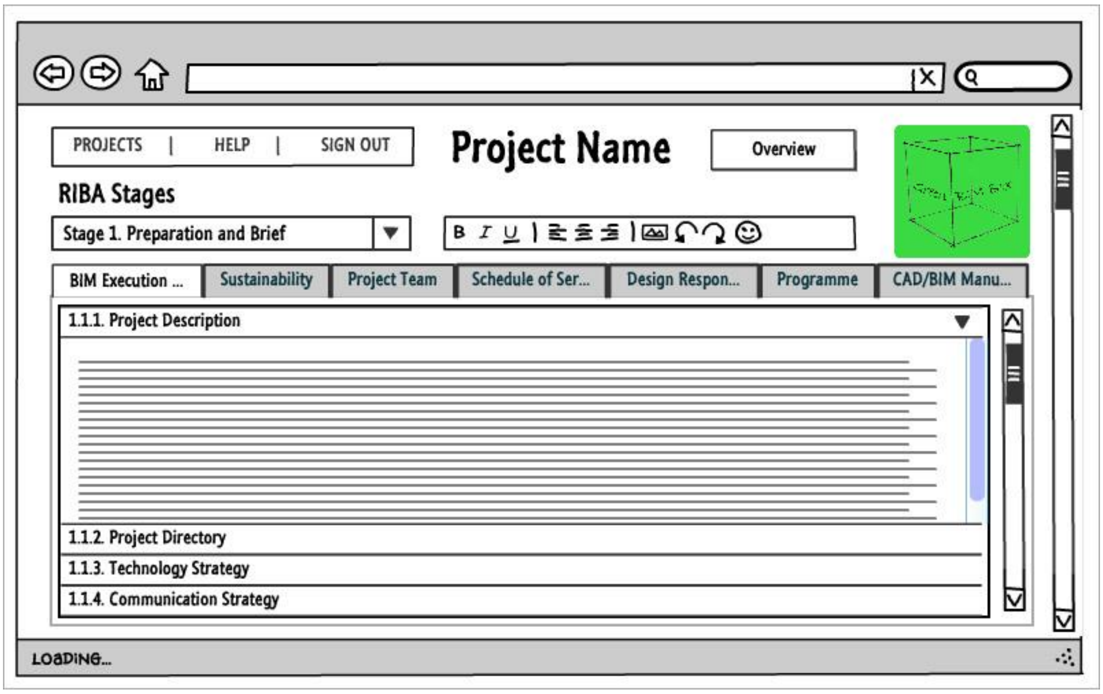


Figure 9 Stage 1 (Preparation and Brief) 1st tab - BIM Execution Plan

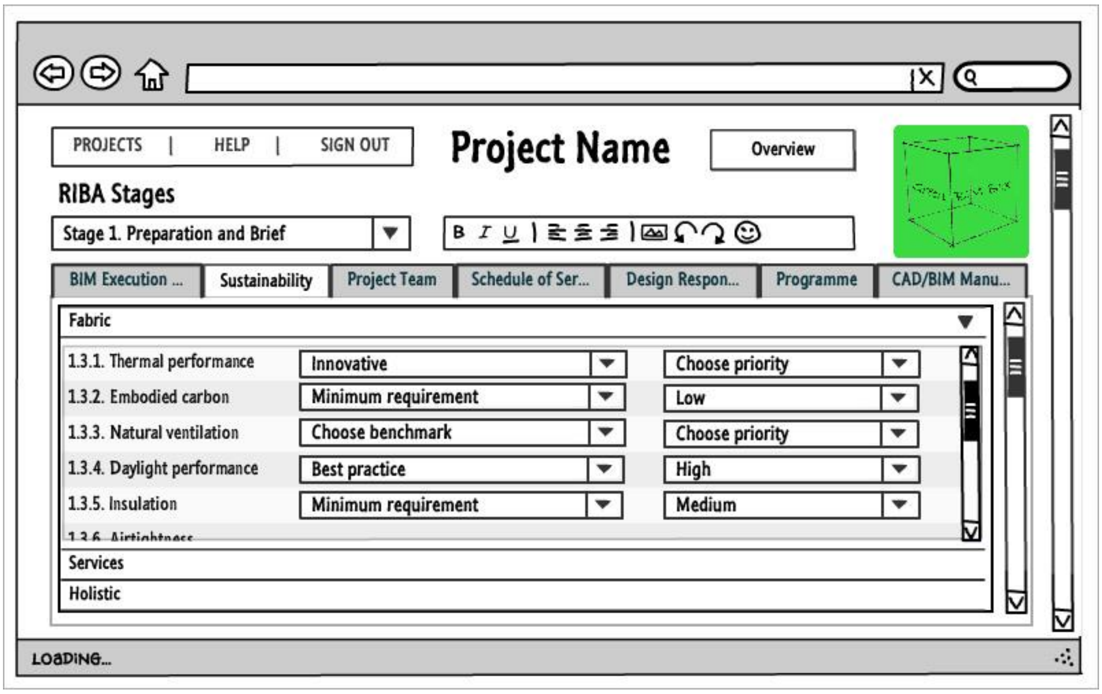


Figure 10 Stage 1 (Preparation and Brief) 2nd tab - Sustainability Objectives

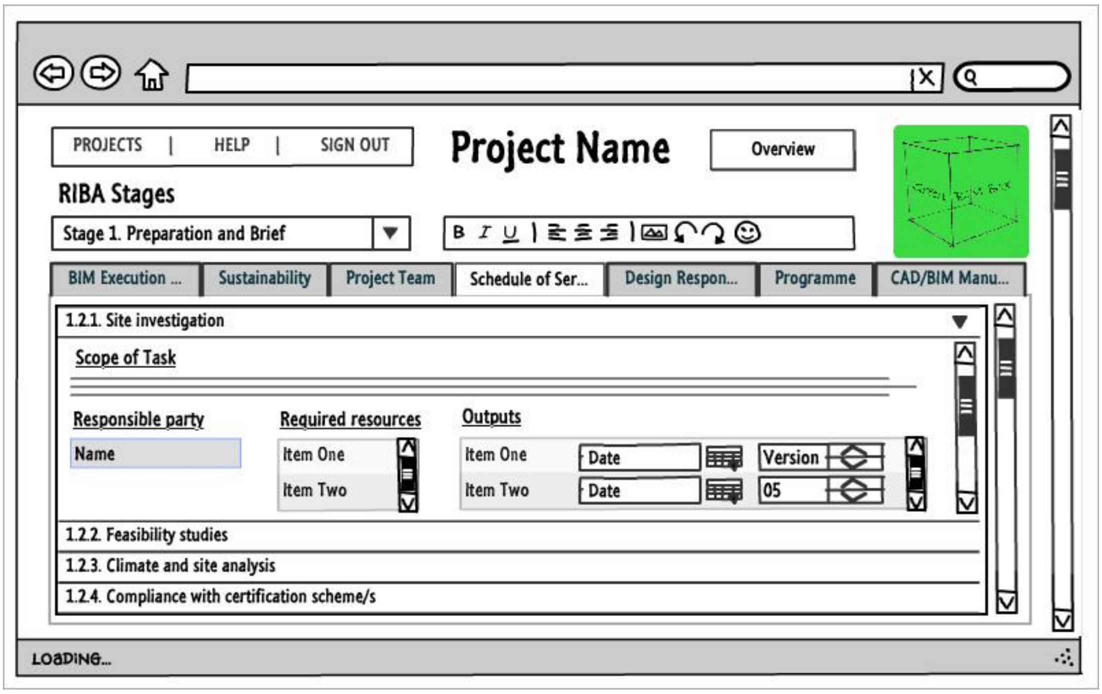


Figure 11 Stage 1 (Preparation and Brief) 4th tab - Schedule of Services

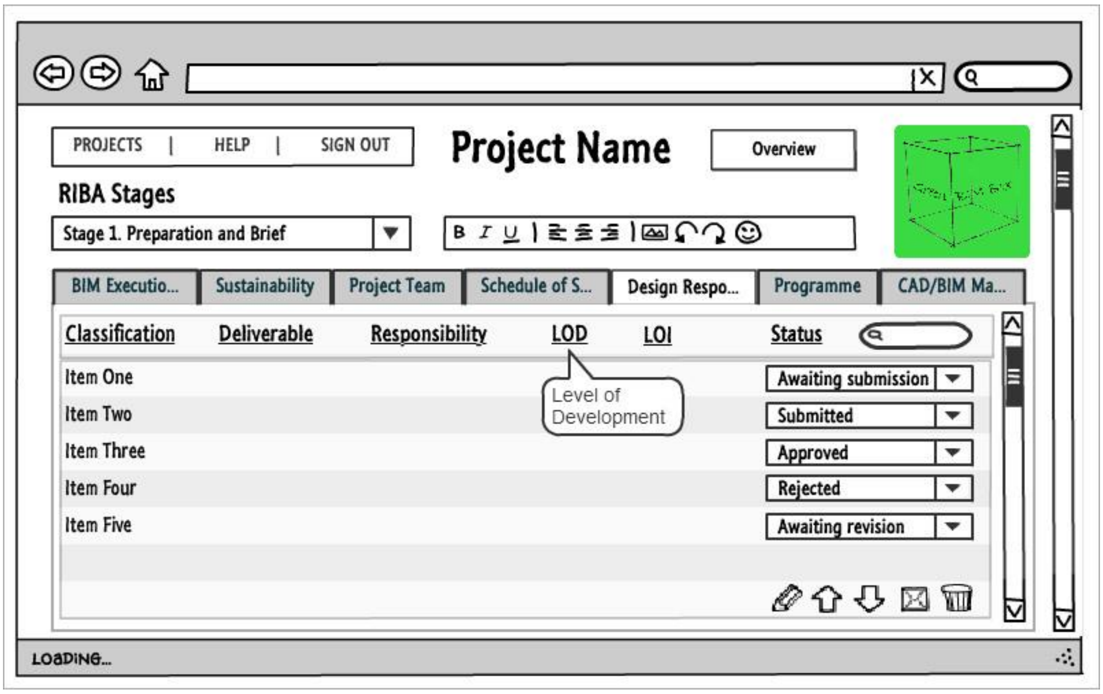


Figure 12 Stage 1 (Preparation and Brief) 5th tab - Design Responsibility Matrix

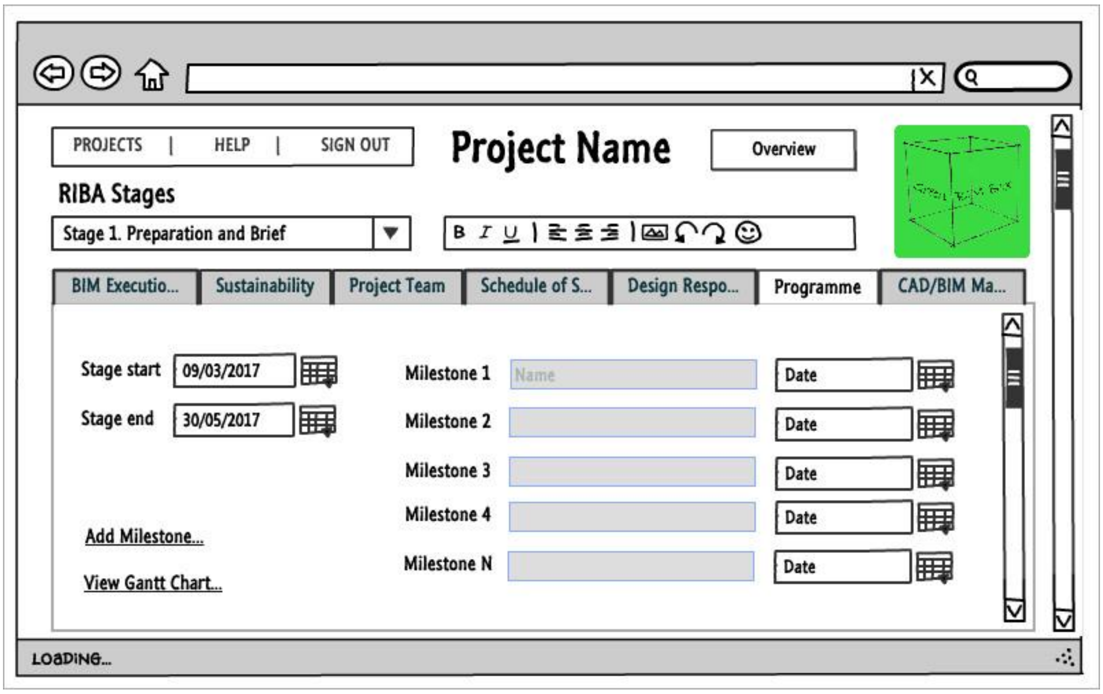


Figure 13 Stage 1 (Preparation and Brief) 6th tab - Project Programme

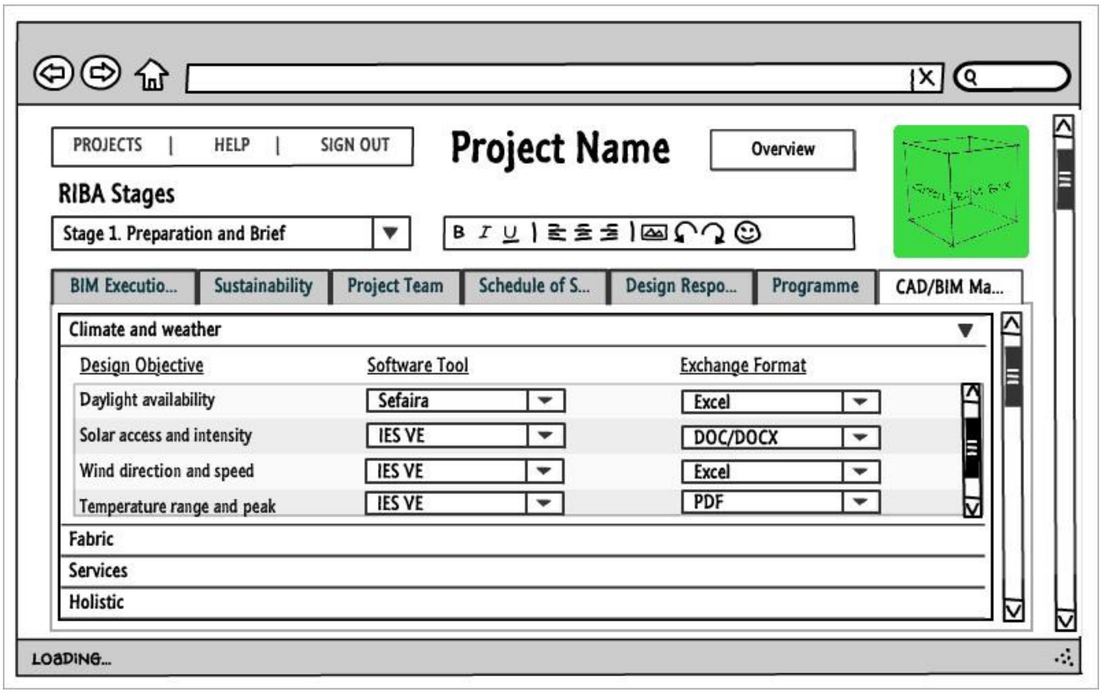


Figure 14 Stage 1 (Preparation and Brief) 7th tab - CAD/BIM Manual (Climate and weather)

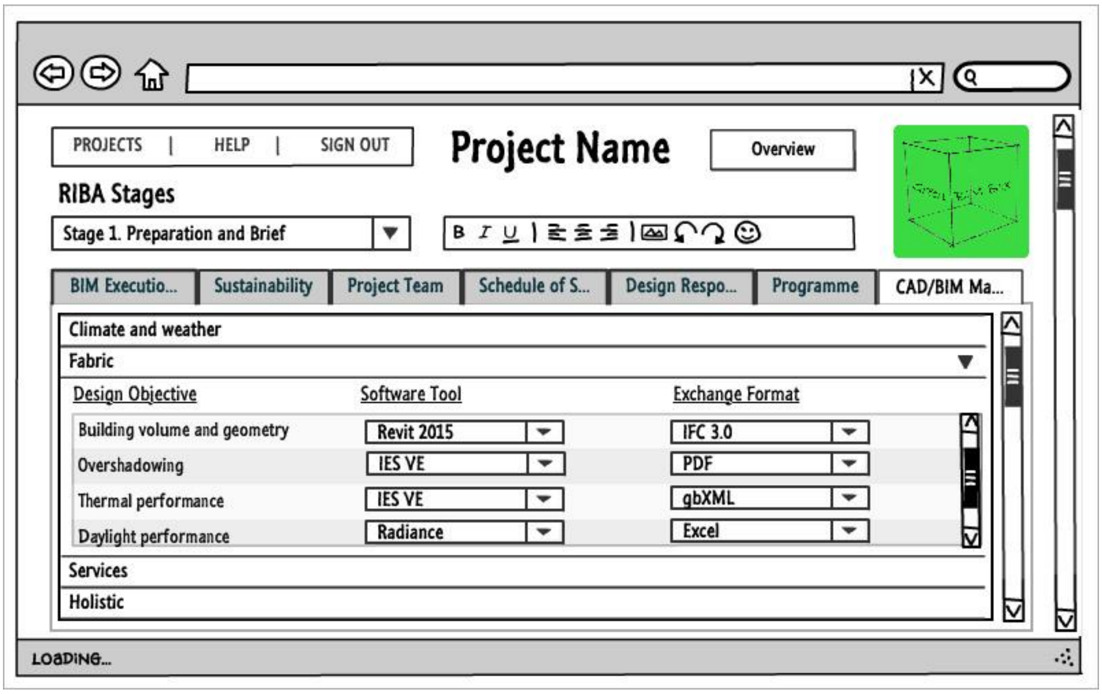


Figure 15 Stage 1 (Preparation and Brief) 8th tab - CAD/BIM Manual (CAD/BIM Manual)

Figures 16 and 17 show snapshots from the "*Sustainability*" and "*Schedule of Services*" tabs of RIBA Stage 2 "*Concept Design*". At this stage, the sustainability performance of the building design is assessed towards the benchmarks set in RIBA

Stage 1. This tab contains the values achieved for each sustainability criterion iteration (latest version). Status updates regarding the approvals of each result are included as described in Figure 12. Notifications/status updates will be sent automatically by the application to the parties involved in this stage. "*Project team*", *"Schedule of Services", "Design Responsibility Matrix", "Project Programme",* and "*CAD/BIM Manual*" contain the equivalent information as described for Stage 1.

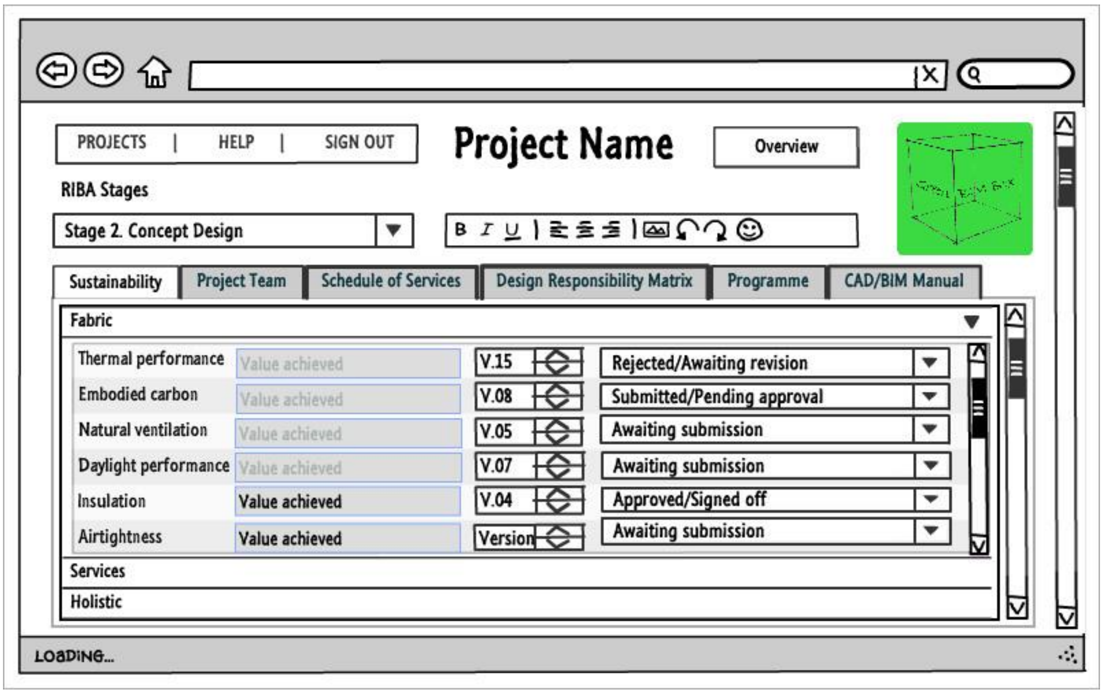


Figure 16 Stage 2 (Concept Design) 1st tab – Sustainability

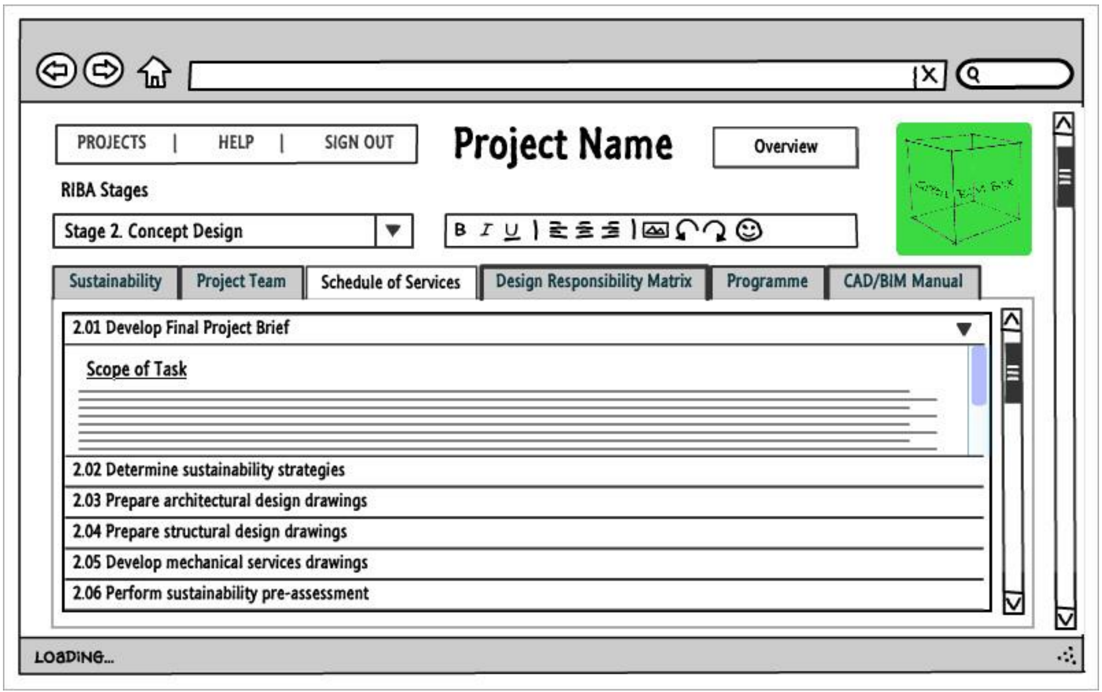


Figure 17 Stage 2 (Concept Design) 3rd tab - Schedule of Services

Figure 18 shows the presentation layer of the application as a Revit plug-in. Through the menu of the toolkit the designer will be able to access their assigned tasks, messages and notifications. Furthermore, they will have the option to connect to the databases linked to the BIM model (data and knowledge layer) in order to upload their work, or download items submitted by other members of the project team. Progress overview may also be accessed through the plug-in, or they may choose the option to open the application in the web browser. On selection of an Entity of the model the user has the option to view attached files, comments, and other attributes (sustainability metrics). A similar process may be created for BPA software tools (e.g. IES-VE). The Entity Relationship Diagram (ERD) (see Figure 19) establishes the links between sustainability attributes and the BIM model's items.

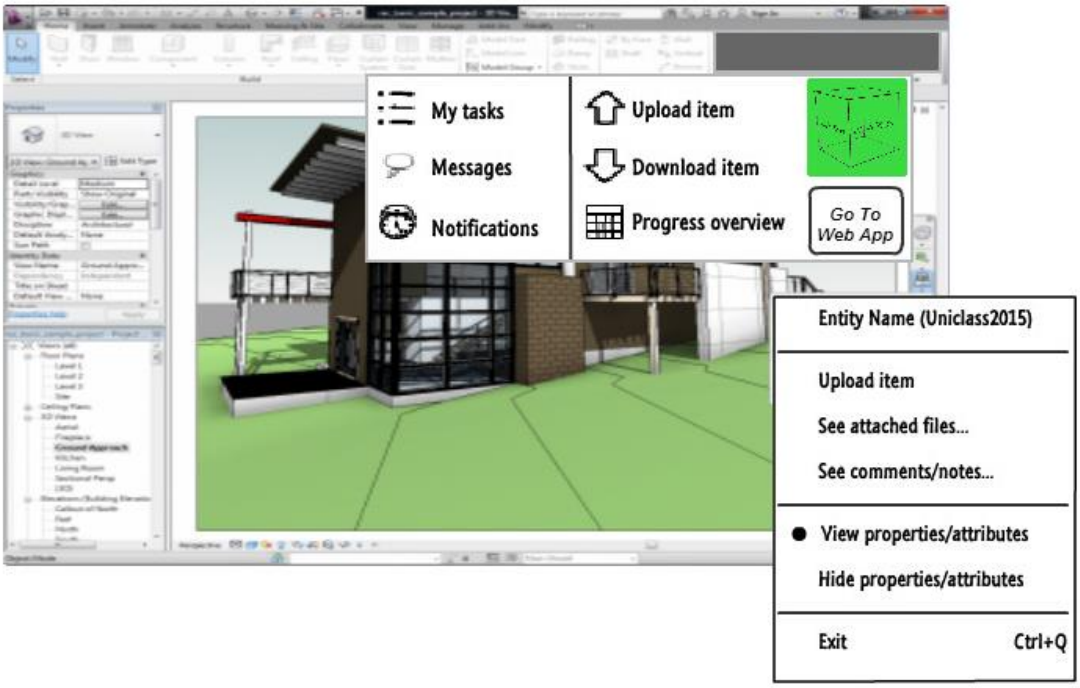


Figure 18 Plug-in presentation layer of the mock-up application (Revit)

B. Service layer: IDEF0/IDEF3 process model

The logical decisions and the commands of the application are situated in this layer. These functions include management, team support, access codes, system's rules, and data mapping. Query management, document management, approval, discussion/messaging, quality management are its main functionalities (Wilkinson, 2005). The IDEF0/IDEF3 process model that has been developed and discussed in Chapters 6 and 7; it contains the rules that guide and control the planning (RIBA Stages 0 and 1) and implementation (RIBA Stages 1 and 2) of the sustainable building design process. Automated asynchronous messages (e.g. notifications) will be send when action needs to be taken or for informing the users regarding constraints or/and progress of the process. To maintain flexibility and adaptability, the administrator will have the option to override the automated process (not restrictive). The received messages can be accessed through the web browser application, the software plug-ins, or the email notifications (optional). Task Based Process Management (TBPM) enables the implementation of dynamic and flexible bespoke processes by identifying the tasks' types and associating agents with them (Chung et al., 2003).

C. Data layer: BIM models' Entities' relationships with sustainability attributes

"A model of the needed data is created based on the types of things about which the system needs to store information (data entities)." (Satzinger et al., 2010)

This section discusses the connections between sustainability information and the BIM models' Entities utilising the Uniclass2015 standardisation (Delany, 2015). The structure of the databases may vary from project to project. Nevertheless, the Entity Relationship Diagram (ERD) (Chen, 1976) focuses on associating the sustainability considerations (within the LOI) as attributes of the Federated BIM model's Entities. This way the information tree is built gradually as the design progresses.

Figure 19 illustrates the sustainability criteria (LOI) associated, as attributes, with each of the above Uniclass2015 standardised deliverables. Climate and Weather attributes need to be provided at RIBA Stages 0 and 1; this information derives by analysing the Complexes' location (e.g. solar intensity, temperature range, wind direction, rainfall, and humidity). This information is essential for the climate analysis to take place and for the designer to be able to estimate which design strategies are the most appropriate. At RIBA Stages 1 and 2, the Entities are designed and the Activities that are associated with them should be stated; this includes overshadowing and energy performance. At RIBA Stage 2 the Spaces (internal layouts) are formed and the Elements of the fabric should be added to the model. The sustainability considerations that take place at this point have to do with the thermal and visual comfort of the Spaces, as well as the performance and specification of materials' properties that are essentially the target values envisioned for each Element. As soon as the considerations about the System that complement the buildings performance take place, the aim is to offset the performance criteria that have not been accomplished by following passive design strategies. The efficiency of building services, equipment and the source of energy are major considerations at this phase. Products are not yet defined by the end of concept design (RIBA Stage 2); those are considerations that take place at the developed design stage (RIBA Stage 3) onwards. Moreover, aspirations about certain products may be discussed at the end of Stage 2 (concept refinement).

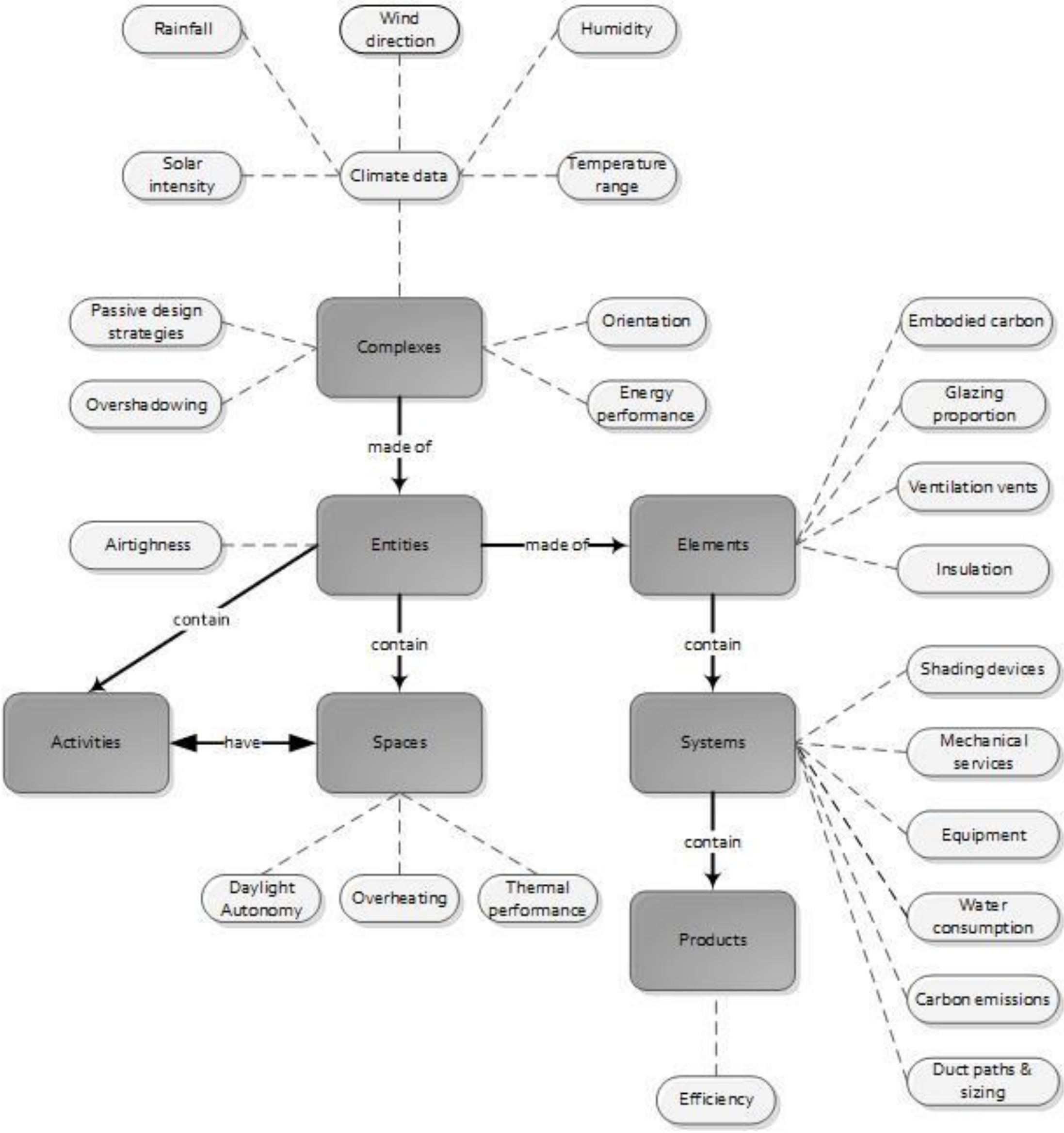


Figure 19 Entity Relationship Diagram (ERD) of a BIM Model (Uniclass2015 classification) aligned with sustainability attributes