2019-05-25

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Recommended Citation

Rogers, J. (2019). *The post-occupancy digital twin: a quantitative report on data standardisation and dynamic building performance evaluation.* Capstone Report. Dublin: Technological University Dublin. doi:10.21427/a37g-ha11

The Post-Occupancy Digital Twin: A Quantitative Report on Data Standardisation and Dynamic Building Performance Evaluation

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Abstract - As a process, originally defined by the UK Government, Level 2 Building Information Modelling (BIM) involves the creation of digital project information, following industry standard guidelines. Through the application of Level 2 BIM, the construction industry can now develop digital representations of physical assets. By combining BIM with digital technologies such as the Internet of Things (IoT), an opportunity is created to link integrated building sensors to these digital representations via advanced Computer Aided Facility Management (CAFM) systems. Successfully combining physical elements to digital elements through a CAFM system results in the creation of Digital Twins (DT), providing an opportunity for dynamic data analysis throughout the capital delivery phase into the operation and maintenance (O&M) phase. A major aspect in the creation of DT involves the ongoing relationship between physical and digital versions of assets. To ensure that physical and digital elements remain aligned, bi-directional updating of data is required. This is achieved through the collection of real-time data via interlinked sensors, generating an opportunity to analyse the performance of the asset and it's occupants. Level 2 BIM provides for delivery of clearly defined project data at intervals of maturity which are termed "data drops". Where project outcomes are poorly defined, the process of digital information delivery often results in a return to traditional methods of data exchange, resulting in static data analysis. Traditional methods of information exchange include graphical and non-graphical data in the form of PDF and Construction Operations Building Information Exchange (COBie) data in Excel format. Static methods of delivering data do not present the DT with the dynamic data required to constantly adapt and reflect the physical version. The aim of this research paper was to determine if the replacement of existing information exchange deliverables with DT can improve building to operations information transfer, and contribute towards greater efficiencies in the post-occupancy operational phase of Level 2 BIM projects in Ireland.

Keywords – Digital Twin, Internet of Things, BIM, Cognitive Environment, Post Occupancy Evaluation

I INTRODUCTION

The McKinsey Report [1] proposed the global construction industry as the second least digitalised and technologically innovated of all industries. The report also discussed that research and development (R&D) investment in construction was less than 1% of revenue, when compared to other sectors, including the automotive and aerospace sectors, with a 3.5–4.5% investment [1]. This suggests that the construction and building sector has not adopted digital technologies in line with other sectors and is still heavily reliant on traditional processes and deliverables [2].

To implement and improve digitalisation of the construction industry, efficient management of data generated from Building Information Modelling (BIM) is critical. Implementation of digital technologies such as Digital Twin (DT) and Internet of Things (IoT) throughout all phases of a building's lifecycle can ensure that buildings are performing as intended, with early identification of any anomalies.

The objectives of this research included:

1. Analysis of each phase of the 2018 Soft Landings Framework and Royal Institute of British Architects (RIBA) Plan of Work 2013;
2. Evaluation of actual operational building performance data against proposed building design calculations in the post-occupancy phase;
3. Analysis of current Level 2 BIM information exchange requirements and deliverables;
4. Development of a roadmap for the creation of DT in alignment with Level 2 BIM requirements.

a) Digital Twin Technology

The Digital Framework Task Group (DFTG) refers to Digital Twin (DT) as *"a realistic digital representation of assets, processes or systems in the built or natural environment"*. This may refer to a real-time updated collection of data, models, algorithms or analysis [3]. A DT is a digital representation of a physical element or product which mimics its real-world behaviour. To create a DT, three main criteria are required:

1 Physical element;
2 Virtual representation;
3 Interconnecting graphical and non-graphical data and documentation to link the physical and virtual [4].

A further nine aspects of DT-enabled service innovation in the manufacturing field were identified by Pourzolfaghar, et al. [5]. They include:

1 Real-time monitoring;
2 Energy consumption analysis;
3 User management and behaviour analysis;
4 User operation guide;
5 Intelligent optimisation and update;
6 Element failure analysis and prediction;
7 Maintenance strategy;
8 Virtual maintenance;
9 Virtual operation [5].

DT differ from other digital models by the connection to a physical element (Fig. 1). As data is uploaded to the DT from the physical asset or system, values are unlocked, which improve decision making and integrate positive feedback with current performance data, into the physical twin via live data flows from sensors [6].

Within BIM projects all information is moved through a central repository called a Common Data Environment (CDE) [7]. Owing to the largely fragmented nature of the industry and multiples variations of preferred software applications in use this represents a significant challenge [8].

Within a DT framework all information relating to the creation and management of DT should be stored in cloud-based data management platforms native to the DT application such as Invicara [9] or Willow [10]. Both platforms are examples of system providers for DT and provide an online platform with a database for non-graphical data and a model viewer for graphical information.

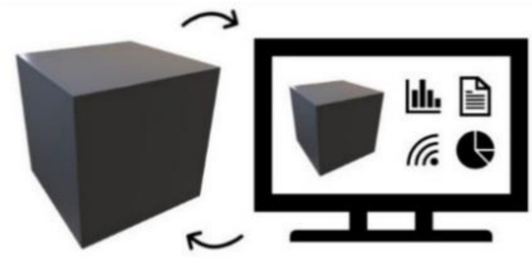


Fig. 1: Overview of a Digital Twin

Fig. 1 displays an example of a Digital Twin by illustrating the connection between the physical element and digital representation through integrated sensor technology.

b) Industry 4.0

Technology can enhance the quality of our lives. This was defined in 2016 by Klaus Schwab, founder of the World Economic Forum, as "*the fourth industrial revolution*" or Industry 4.0 [11]. Further development of the internet has led to the creation of an interconnected network of devices commonly referred to as the Internet of Things (IoT). Examples of connected devices range from portable devices such as mobile phones and tablets to Radio Frequency Identification Device (RFID) building sensors and Global Positioning System (GPS) devices [12].

One of the many benefits of DT is the ability to update data in real-time with any changes in the physical object. This is achieved by connecting the DT to physical elements via sensor technology and IoT [13]. Sensors in a building can collect data relating to the internal environment, such as temperature and carbon monoxide levels. This information is referred to as "big data". Big data requires the implementation of data management strategies, leading to increased efficiency in data retrieval by focusing data analyses locally and reducing large volumes of data relating to the DT [14]. The evolution of IoT has led to an increase in sensorisation of physical spaces, resulting in growing functionality of applications such as Building Management Systems (BMS) that acquire data relating to the surrounding environment in real-time [15]. BMS can be improved further by integration with BIM to digitally represent physical and functional characteristics of physical spaces providing current information about the building and environment [16]. A study by Dave, et al. [17] described the development of a platform to integrate built environment data with IoT sensors. Information relating to occupancy, user comfort and energy usage was integrated with BIM and IoT devices through Industry Foundation Classes (IFC) models and open messaging standards. This research collected data relating to occupied building spaces and provided data to the occupants on a mobile application ensuring they had instant access to real-time building usage data [17].

c) Dynamic Building Performance Evaluation

By implementing digital technologies such as DT and IoT into current or existing projects, an opportunity is created to monitor and improve the performance of a building, and in time, the built environment (Fig. 2). Research by Royapoor et al. [18] has shown that vast savings can be made by implementing these technologies, and as pricing relating to sensors and technology reduces, the construction industry can expect greater savings on a variety of projects in the future [18].

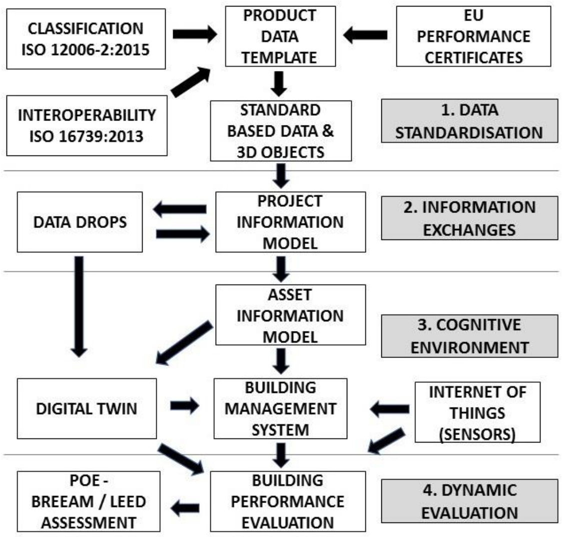


Fig. 2: Dynamic building performance evaluation

Fig. 2 displays an overview of the process required for the creation of a cognitive environment through the standardisation of data throughout the design process. The results of this process are a dynamic building performance evaluation analysis through integrated sensor technology.

II LITERATURE REVIEW

A literature review was adopted to address objectives one, two and three by reviewing peer assessed academic papers, industry standards, guidelines and recent publications.

a) The Gemini Principles

Digital technologies can enhance the delivery and maintenance of assets by creating and managing data generated through digital construction. The role of DT in the creation of smart cities and high performing assets, using connected data, was recognised by the Centre for Digital Built Britain (CDBB), leading to the creation of a framework for a "Digital Built Britain". This framework included the publication of The Gemini Principles [3] along with the publication of a roadmap for delivering the information management framework for the built environment [19]. The Gemini Principles were published in December 2018 by the Digital Framework Task Group (DFTG) on behalf of the CDBB. The Gemini Principles (Table 1) address key recommendations in the National Infrastructure Commission's report "Data for the public good" [20].

By identifying DT as a means to enable better use, operation, maintenance, planning and delivery of assets, systems and services, the CDBB proposed the creation of a National Digital Twin (NDT) [3]. The core focus of this research paper is the standardisation of data with a focus on Gemini Principle number 5 (Openness) which relates to the creation of open data.

An essential aspect for DT is Openness (Gemini Principle 5; Table 1). Openness encourages the sharing of data amongst project collaborators and the creation of trust through collaborative modelling. Open standards ensure that data extracted from digital models is readable by software applications supporting an open standard such as IFC. Open standards facilitate collaboration between disciplines, allowing for exchange of data regardless of what application the data was created in [21].

Table 1: The Gemini Principles

The Gemini Principles		
Key Statement	**Gemini Principle**	
Purpose:	1.	Public good
	2.	Value creation
	3.	Insight
Trust:	4.	Security
	5.	Openness
	6.	Quality
Function:	7.	Federation
	8.	Curation
	9.	Evolution

Table 1 displays the Gemini Principles with Gemini Principle 5 – "Openness" Highlighted.

Data generates value when it is contributed to and maintained. In order to generate the most value from the NDT, it must be as open as possible, whilst retaining security principles identified in Publicly Available Specification (PAS) 1192-5 [22]. This can be achieved by developing an open culture within industry through the implementation of international standards and the development of interoperable Application Programming Interfaces (API), allowing a vendor-neutral approach [23].

To create openness, and fully benefit from the creation of a DT, data must be consistent and structured. Baron [24] reported that structured data ensures Building Management Systems (BMS), such as Maximo by International Business Machines (IBM), can interpret data and associate said data with corresponding elements within the model during the operational phase [24]. According to Kaseem et al. [25], the operational phase is the main contributor to the lifecycle cost of a building. It has been found that the life cycle cost can vary between five to seven times of the initial cost of the building [25]. These figures show that operation and maintenance of a building must be prioritised within the design process, as it is then that challenges are identified relating to data management. The availability of different BIM authoring tools (Revit, ArchiCAD and Tekla) has led to inconsistent data flow between disciplines. Examples identified by Mecheri and West [26] include inconsistent modelling practices and construction data and a lack of adherence to standardised classification systems. To ensure accurate data transfer between future software systems, all data should be consistently structured ensuring a seamless flow between all disciplines involved in a project [26].

Management and digitisation of data is essential for successful implementation of DT. To achieve this, data needs to be traceable and consistent, follow international standards, pre-defined data structures and definitions. Andriamamonjy et al. [27] reported that open BIM is currently being standardised by two technical European committees CEN/TC 442 (European Committee for Standardization) and ISO/TC 59/SC 13 (Organization and digitization of information about buildings and civil engineering works, including building information modelling (BIM)) [27]. International standards involved in the creation of open BIM and Product Data Templates (PDT, Fig. 3) include classification (ISO 12006-2:2015) and interoperability (ISO 16739:2013). Classification of objects in the model ensures information is easily accessible and managed throughout the project [28], while interoperability ensures that data is available in multiple formats, languages and software tools [29].

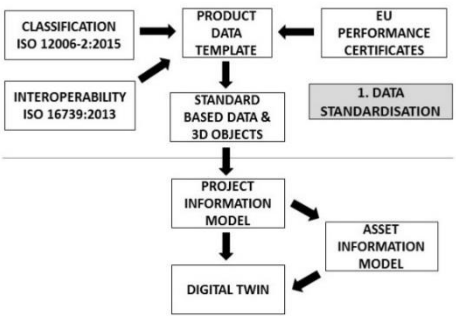


Fig. 3: Standardisation of data

Fig. 3 demonstrates how structured data created through PDT is developed during the design stages.

d) *Standardisation of Data*

Data standardisation can be achieved through the creation of PDT (Fig. 3). PDT adhere to European Harmonised Standards, resulting in a Declaration of Performance (DoP) certificate for construction products in compliance with the Construction Products Regulation (CPR) [30].

Product performance data is combined in a common technical language known as Digital Data Dictionaries (DDD). With DDD, information relating to product performance from different countries can be amalgamated to create a database of current material properties including: structural stability, fire resistance, acoustic properties and energy efficiency [31]. An example of such a definition was described by Farghaly et al. [32] in relation to a u-value (Fig. 4). A u-value is a measurement relating to thermal performance, or heat loss through a material or building element. Different countries have different definitions relating to the transfer of heat, as a u-value is sometimes referred to as thermal transmittance. The DDD framework enables BMS to read the data irrespective of geographical location, by mapping similar definitions in the DDD to unique codes in the BMS, ensuring the values are correct [32].

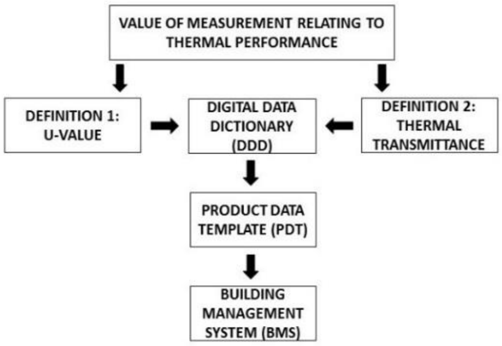


Fig. 4: Digital data dictionaries

Fig. 4 displays an example of alternative definitions combined into a universal definition through DDD.

Sharing of structured data is crucial for the creation of DT. Implementation of international standards can lead to the creation of interoperable data, which can be distributed between multiple operating systems, eliminating design data silos. The creation of PDT ensures a common data structure which manufacturers can populate with up-to-date product information. Examples of PDT include the BIM Databook by the Building Research Establishment (BRE) [33] and GoBIM, which is provided by Cobuilder [34].

e) *Asset and Information Management*

Asset management generates value from assets by converting business objectives into asset-related decisions throughout the asset's lifecycle [35]. An Information Management Process (IMP) is created in accordance with standard processes and procedures identified in BS ISO 55000 (Fig. 5), which was used to develop United Kingdom (UK) BIM standards including PAS 1192-2:2013 and PAS 1192-3:2014. These standards relate to the creation and management of building information. PAS 1192-3:2014 provides guidance on managing the Asset Information Model (AIM) post-handover by linking to enterprise systems (BMS) such as Maximo [36].

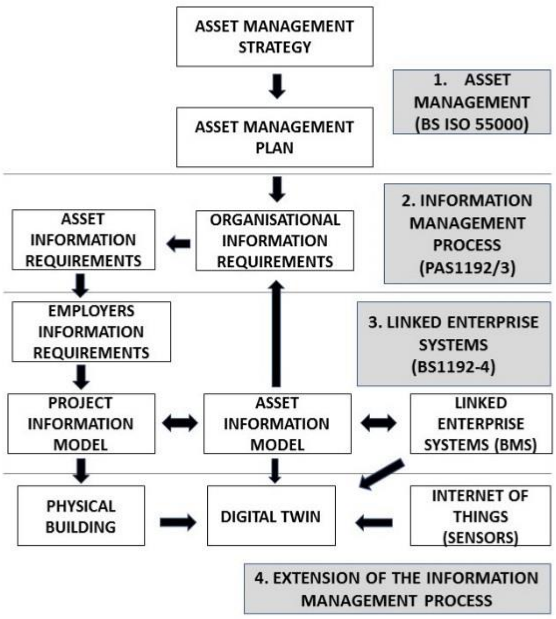


Fig. 5: Information management process

Fig. 5 illustrates how the information management process is extended to include the Digital Twin, created by linking the physical model to the digital model through IoT following project completion and handover of the AIM.

f) *Level 2 BIM - Information Exchange Require-ments*

Since 2016, Level 2 BIM is a requirement for all Government buildings in the UK. Level 2 BIM involves the creation and management of digital assets in compliance with the PAS 1192-2 suite of documents [37].

The Level 2 BIM process involves the creation of vast volumes of data generated and developed across the full lifecycle of the asset from design through construction into operations and handover. This information is often un-coordinated and not fit for immediate translation to the Operations and Maintenance (O&M) phase at project handover due to interoperability issues relating to BIM technologies and Facility Management (FM) systems [25].

The information delivery cycle (Fig. 9, Appendix A) is introduced in PAS 1192-2:2013 and represents all stages of a BIM project in alignment with the Royal Institute of British Architects (RIBA) Plan of Work 2013 (Table 2). PAS 1192-2:2013 requires information exchanges, also referred to as "data drops", at designated intervals during the design phase [36]. Data drops, as outlined in PAS 1192:2 are a staged mechanism for approval of project information against Employer's Information Requirements (EIR) which are aligned to contractual levels of project maturity. As the project progresses, the information contained as attributes within the model increases.

Table 2: RIBA Plan of Work 2013

RIBA Plan of Work 2013	
Briefing	
Stage 7	In Use
Stage 0	Strategic Definition
Stage 1	Preparation & Brief
Design	
Stage 2	Concept Design
Stage 3	Developed Design
Construction	
Stage 4	Technical Design
Stage 5	Construction
Stage 6	Handover & Closeout

Table 2 displays the RIBA Plan of Work (2013) which arranges building projects into a number of key stages such as briefing, design and construction.

g) *Level 2 BIM - Information Exchange Deliverables*

Documentation is defined by the British Standards Institute (BSI) [36] as "*information for use in the briefing, design, construction, operation, maintenance or decommissioning of a construction project*". Data drops contain documentation (drawings, schedules, specifications and spreadsheets), along with graphical and non-graphical data for each stage of the project.

In 2019, ISO19650-1 and ISO19650-2 were published. These standards were founded on the UK's BIM standards; BS 1192:2007 + A2:2016 and PAS 1192-2:2013 and relate to the management of information using BIM. This represents a major step for BIM as it advances from a PAS document to an internationally recognised standard. One of the changes contained in ISO19650-1 involves the renaming of graphical and non-graphical data to alphanumerical information, and geometrical information (Table 3, Page 6) [38].

Table 3: Information Exchange Requirements

Information Exchange Comparison	
PAS 1192-2:2013	**ISO19650-1:2018**
Documentation	Documentation
Non-Graphical Data	Alphanumerical information
Graphical Model	Geometrical information.

Table 3 displays a comparison between information exchange requirements in PAS 1192 and ISO19650-1

Graphical data is defined by BSI [36] as *"data conveyed using shape and arrangement in space"*. Examples of graphical data include native three-dimensional (3D) models and interoperable IFC files. Non-graphical data is defined by BSI [36] as "data conveyed using alphanumeric characters". Examples include: Construction Operations Building Information Exchange (COBie) data in Excel in accordance with BS1192-4:2014 [39].

COBie is an open database containing information for the operation, maintenance and management of the asset by the FM [40]. When COBie is required for information exchange, COBie data should be extracted from the BIM model using an Autodesk BIM interoperability COBie extension tool in Excel format for linking into a Computer Aided Facility Management (CAFM) system [41]. Although COBie is identified as a BIM Level 2 deliverable, O'Sullivan and Behan [42] showed that COBie data was not included in over 70% of cases surveyed and indeed highlighted that the safety file for the Grangegorman Greenway Hub was handed over via compact disc [42].

h) RIBA Plan of Work 2013

RIBA Plan of Work 2013 Stages 7, 0 and 1 relate to briefing and initial design stages. By starting with Stage 7, emphasis is placed on incorporating lessons learned from previous projects into current and future projects through feedback and data analyses [43].

Harnessing the results from Post-occupancy Evaluation (POE) and Building Performance Evaluation (BPE) can lead to improved efficiency in the early project stages through better decision making and planning, ensuring the best possible platform for design stages. Stage 0 involves the creation of project documentation including the BIM Execution Plan (BEP), while the creation of a CDE in Stage 1 enables multi-discipline collaboration [44].

RIBA Plan of Work 2013 stages 2 and 3 emphasise the needs of the client and ensure that project outcomes are identified and achievable through the creation of concept models. Project programme, budget and procurement strategies are put in place, along with concept models to create a co-ordinated design between disciplines, suitable for planning submittal [45].

RIBA Plan of Work 2013 stages 4, 5 and 6 encompass the final stages of the project. Stage 4 involves finalising documentation for commencement of construction in Stage 5. Following construction, the asset is handed over to the client in Stage 6 with the Project Information Model (PIM). The PIM developed during the project is now referred to as the AIM. The AIM contains digital data relating to the maintenance of systems in the building, Health and Safety (H&S) information, as-constructed information and live links to data within the model [46]. Following the creation of standardised data from PDT's during the design stages, the AIM can now be linked to the BMS, leading to the development of a Digital Twin (DT, Fig. 3). It was proposed by Jarvinen [47] that DT are not only representations of a real building, but of a building's components, systems and functionalities. DT can act as a user interface for AIM (Fig. 6), ensuring that information from multiple disciplines can be viewed and operated through a single interface [47].

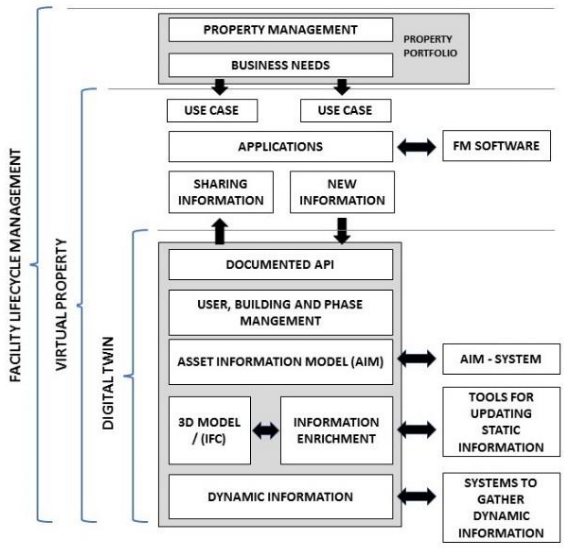


Fig. 6: Facility lifecycle management [47]

Fig. 6 illustrates how Digital Twin can act as a user interface for the Asset Information Model (AIM).

i) Soft Landings

When Level 2 BIM was mandated in the UK (2016), one of the supporting frameworks was Government Soft Landings (GSL), also referred to as Soft Landings (SL). SL ensure that BIM is implemented in current and future developments to support Facility Management (FM) throughout the Operations and Maintenance (O&M) phase of an asset [48].

In 2018, the SL Framework 2014 [49] was updated [50]. One of the main changes was the replacement of the term "Stage" with "Phase". This change was implemented to ensure SL are not related to any plan of work, but rather to activities occurring during certain phases of a project [50]. The other main change was the replacement of five stages (2014) with six phases (2018), with an extra phase added for RIBA Stage 5 (Construction) (Table 4).

Table 4: A comparison of SL 2014 and 2018

Soft Landings 2014 and 2018 Framework

RIBA Stage	Soft Landings 2014	Soft Landings 2018
0	Stage 1. Briefing	Phase 1. Inception and briefing
1		
2	Stage 2. Design development	Phase 2. Design
3		
4		
5		Phase 3. Construction
6	Stage 3. Pre-handover	Phase 4. Pre-handover
7	Stage 4. Initial Aftercare	Phase 5. Initial Aftercare
	Stage5. Years 1 to 3 Aftercare:	Phase 6. Extended Aftercare and POE

Table 4 compares stages and phases between the 2014 and 2018 SL Framework's with the additional phase (Phase 3) highlighted.

SL help the project team focus on client requirements, throughout the project, by smoothing the transition from RIBA Stage 0 (Strategic Definition) through to RIBA Stage 7 (In Use). Key features of SL include:

1 A reduction in cost while improving performance and delivery of assets;
2 The creation of a 'golden thread' of information throughout the design and construction stages, through to building operation;
3 Early end user involvement in the project;
4 Analysis of asset performance through POE and BPE analysis;
5 Creation of a fully populated AIM and supporting data to link into CAFM system [51].

j) Post-Occupancy Evaluation (POE)

Following building handover in Stage 6 (Handover and Close Out), a three-year POE analysis is performed (Table 5).

Table 5: Post-Occupancy evaluation stages

RIBA Plan of Work 2013 Stages

Stage 6	Stage 7		
Handover	Post-occupancy Evaluation		
	Year 1	Year 2	Year 3

Table 5 displays the three-year POE phase following project handover.

The extended aftercare phase of SL focuses on the operation and occupancy of the building for a period of three years. The main aim of Year 1 is to ensure that the design intent is realised, to assess the performance of the building in light of operation during each season, and to identify any problems through logged data, end user feedback and informal interviews. Measurements relating to the indoor environment including temperature, humidity and air quality, should be recorded three months after occupancy to create a general imprint of building performance, and, to help identify potential occupational and operational problems. Systems such as lighting control and Heating, Ventilation and Air-Conditioning (HVAC) may need to be optimised for improved energy-efficiency [18]. Feedback from end users and weather data should be logged for comparison to actual building heating requirements. Metering data should be checked to ensure accurate readings are recorded.

In Years 2 and 3, the reviews become less frequent and are focused on the operation of the building, Post-Occupancy Evaluation (POE) and fine-tuning. POE studies typically include occupant satisfaction surveys along with technical and energy performance evaluations. The type, coverage, method and timing of POE studies depends on initial project agreements [50]. Ideally, a POE should take place 12 to 18 months after occupancy and then repeated, if necessary, 36 months after occupancy. The main objectives of this phase are to:

- Assess building performance against defined success criteria;
- Address and solve identified problems;
- Optimise the operational performance;
- Capture and disseminate lessons learned.

An example of where POE and BIM were utilised was the construction and delivery of a new Enterprise Centre on the University of East Anglia (UEA) campus [52]. The Building Services Research & Information Association (BSRIA) implemented SL and provided POE support including life cycle costing, airtightness testing and thermal imaging analysis. The Enterprise Centre Estates team were engaged from the design stage through to completion and worked with the design team and building occupants to ensure that the building met expectations after handover. The handover process was planned ahead of completion, which ensured all staff were pre-trained in the operation of the building and building systems. An example of one building system is ventilation. As no artificial cooling is provided on the main floor areas, windows are the only source of ventilation. Controls are located on the windows which included indicator lights to advise occupants when it is necessary to open and close windows [52].

k) Building Performance Evaluation (BPE)

A BPE provides an overview of which aspects of the design, construction and installation were, or were not, effective. BPE gives building owners and FM an opportunity to identify problems relating to the building's operational systems. BPE studies can also help in the development of a robust database for benchmarking purposes that may assist the wider built environment. Along with providing feedback for future developments, BPE can reduce running costs, optimise building performance and increase occupants' satisfaction.

The actual performance of a new or refurbished building can be very different to the design intent. Discrepancies in energy use and occupant comfort can arise from a variety of sources including construction quality and building services installation [50]. The gap between actual and expected performance of buildings continues to be an issue. A contributing factor is the non-involvement of construction teams in operation and limited feedback from the occupiers. BPE can play a vital role in facilitating this feedback and help to close this gap. The test methods and techniques employed in a BPE study should be selected appropriately. Some commonly used methods are:

- Physical testing of building fabric;
- Physical testing of mechanical services;
- Energy assessment;
- Understanding user perception;
- Indoor environmental quality (IEQ) evaluation [53].

Using Digital Twin (DT) and Internet of Things (IoT) to measure real time environmental conditions can lead to increased building performance and energy. Lee et al. [54] utilised BIM as an energy monitoring system through the implementation of Autodesk Revit. Revit allows end-users to acquire and monitor building energy data. Data was obtained from sensors monitoring geothermal energy and lighting and an energy baseline was established. Energy-saving procedures were implemented to improve the existing heating system, control HVAC and lighting, resulting in an overall reduction in energy consumption of 12% [54]. Presidion [55] reported a feasibility study conducted by Tesco Ireland along with International Business Machines (IBM). Data collected on this joint study identified variations in refrigerator temperatures in their stores. To rectify this, an improved process was required to ensure refrigerators continuously operated within optimal temperature ranges. Data was acquired and predictive analytics was used to validate refrigeration performance. By applying the results from one store, refrigeration performance was validated, and any anomalies were identified, leading to a reduction in total energy costs. Operation of freezers at the optimal temperature generated a net saving of 20% in overall energy cost, namely 25 million pounds a year throughout the UK and Ireland [55].

l) Building Research Establishment Environmental Assessment Method (BREEAM)

BREEAM offers a verifiable and independent assessment of the performance of building design and construction over three stages: Pre-assessment, Design stage assessment and Post-construction stage assessment [56]. BREEAM certification levels are divided into six categories:

1 Unclassified;
2 Pass;
3 Good;
4 Very Good;
5 Excellent;
6 Outstanding.

Areas focused on during a BREEAM examination include:

- Visual comfort;
- Acoustic performance;
- Indoor air quality;
- Water consumption;
- Thermal comfort;
- Reduction of CO_2 and N_2O levels;
- Energy monitoring;
- Low and zero carbon technologies;
- Reduction of night time light pollution;
- External lighting;
- Energy efficient equipment;
- Water monitoring;
- Insulation,
- Emissions;
- Sourcing of materials [56].

Buildings that achieve a BREEAM rating of Excellent or Outstanding are required to undergo a BREEAM In-Use Assessment within three years of completion in order to maintain their rating and certify ongoing performance. This encourages the continued high performance of the building, even after occupation. An example of a BREEAM "Outstanding" building is the Central Irish Bank in Co. Dublin, Ireland, which was awarded the BREEAM Outstanding rating for sustainability in 2017. Achievement of this standard was centred on an intelligent HVAC system linked to a BMS. The ventilation strategy involved linking louvers in the facade and internal $C0_2$ sensors to the BMS. When CO_2 levels reach 900 parts per million, the sensors inform the BMS to activate the louvers, allowing fresh air into the building. Meeting rooms are controlled by ventilator sensors to monitor the supply of incoming air. Ventilators have Passive Infrared Sensors (PIR) that detect motion and shut the ventilator down if the room is left unoccupied. In addition, the lighting system contains photocells on each Light-Emitting Diode (LED) which turn the light on when natural light levels fall below a programmed lux level. Each LED light is fitted with a PIR sensor to detect motion [57].

m) Leadership in Energy and Environmental Design (LEED)

LEED is a sustainable rating system for buildings. LEED certification levels are divided into four categories:

1 Certified;
2 Silver;
3 Gold;
4 Platinum.

Certification is achieved following assessment of the following areas:

- Sustainable sites;
- Water efficiency;
- Energy and atmosphere;
- Material selection;
- Indoor environmental quality;
- Innovation and design process [58].

Research undertaken by Jalaei and Jrade [59] identified problems relating to delivery of sustainable designs through LEED by conducting full building energy simulation, acoustical analysis, and day lighting analysis. To resolve these issues, it was proposed to integrate BIM with LEED for buildings at the conceptual design stage by automating LEED certification categories and allocating points relating to individual categories [59].

n) Actual Operational Building Data vs Proposed

BIM enables the development of a semantic association between object geometry and information [60]. By combining static information (BIM) with dynamic information (IoT), a cognitive environment is developed, which encompasses physical buildings with technology. This provides the asset with cognitive capabilities, allowing it to learn from previous tasks and to re-apply that same learning to the subsequent task.

The stages and deliverables involved in a Level 2 BIM project are summarised in Table 6 (Page 10). Table 6 indicates how the Project Information Model (PIM) converts to an Asset Information Model (AIM) at project handover. It also shows when creation of the DT starts, when construction is complete, and when sensors are inserted into the building. POE is indicated for stage 7, along with BREEAM evaluation collecting static information until sensors are introduced in stage 6. The BREEAM evaluation can now start collecting dynamic information from the building sensors relating to building performance and generate accurate real time data for evaluation.

A study by Teizer et al. [61] focused on providing real-time energy performance data to workers in an indoor work environment. This was achieved by integrating BIM technologies with IoT information sources and Radio Frequency Identification Device (RFID) sensors. The BIM was synchronised with lighting and proximity IoT sensors, providing workers with real-time environmental conditions. Results demonstrated successful integration of connected digital technologies, highlighting the potential that connected technologies can provide to post-occupancy O&M processes [61].

Ciribini et al. [62] devised a cognitive environment linking BMS to a BIM environment by collecting real time data from sensors measuring building heating, lighting and energy usage [62]. Another example of this association is Project Dasher by Autodesk which combines physical building components with real-time project data (Fig. 7). Sensors are inserted into rooms to capture data relating to energy consumption, CO_2 levels, humidity, temperature and occupancy. These sensors are represented in an online browser and display an overview of sensor information ranging from minutes to months [63].

Fig. 7: Autodesk Dasher 360 [63]

Fig. 7 displays Autodesk Dasher 360. Dynamic data is generated through building sensors and displayed in an online 3D model with real-time data feed and analysis.

Table 6: Dynamic building performance evaluation

RIBA PLAN OF WORK 2013	Stage 0	Stage 1	Stage 2	Stage 3	Stage 4	Stage 5	Stage 6	Stage 7
LEVEL 2 BIM DELIVERABLES								
Common Data Environment	■	■	■	■	■	■	■	■
Project Information Model		■	■	■	■	■	■	
Asset Information Model					■	■	■	■
INTEGRATION OF DIGITAL TECHNOLOGIES								
On-Site Construction						■		
Internet of Things						■	■	■
Digital Twin					■	■	■	■
BUILDING PERFORMANCE EVALUATION / ANALYSIS								
Static Information Collection	■	■	■	■	■	■		
Dynamic Information Collection						■	■	■

Table 6 illustrates the relationship between the RIBA stages, POE and building analysis. Dynamic evaluation is identified as a replacement to static evaluation after Stage 5 – Construction.

III METHODOLOGY

Design Science (DS) was defined by Hevner et al. [64] as *"the creation and evaluation of IT artefacts intended to solve identified organizational problems"* [64]. Peffers et al. [65] developed a Design Science Research Methodology (DSRM) framework for the production and presentation of DS research information. The DSRM framework includes six steps:

1 Problem identification;
2 Defining objectives for solution;
3 Design and development;
4 Demonstration;
5 Evaluation;
6 Communication.

In addition, Offermann et al. [66] illustrated a research process which optimised existing DS processes. The process implemented on this research involved combining the DSRM framework with a combination of qualitative and quantitative research methods including literature reviews, surveys and interviews [66]. The methodology adopted for this paper incorporates the DSRM framework of Offermann et al [66], which is in turn based on the DSRM framework developed by Peffers et al. [65] (Fig. 8).

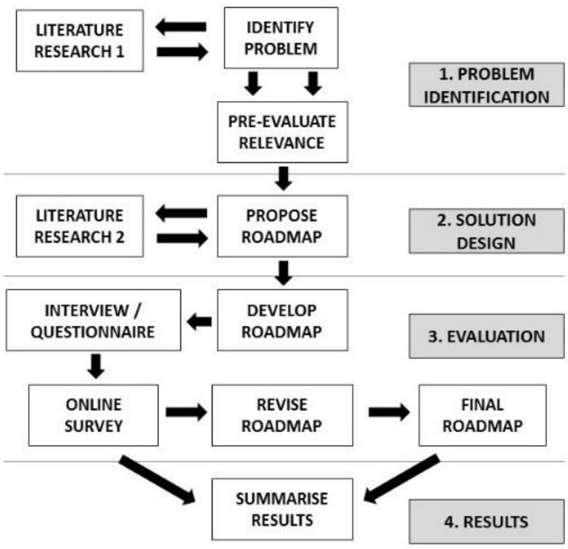


Fig. 8: Schematic of the project DSRM framework

Fig. 8 outlines four phases of DSRM utilised in research including:

1 Problem identification;
2 Solution design;
3 Evaluation;
4 Summary of results.

a) Ethics, General Data Protection Regulation (GDPR) and Data Management

Summarised results are presented in this report, which ensures no individually identifiable information is distributed. All participation was voluntary, and no encouragement was provided during completion of the questionnaires or surveys. All participants signed a form of consent which was in compliance with GDPR regulations and included the following:

- The right to withdraw from the study;
- Confidentiality of information;
- Anonymity of questionnaire;
- The right to withdraw data.

b) Interview Questionnaire

Findings from the literature review, along with the creation of a roadmap (Appendix D, Fig.11: RIBA Plan of Work 2013 - Stage 0 to Fig. 18: Stage 7), led to the design of twelve interview questions. These questions, along with the roadmap, were distributed by email to ten personnel who were chosen due to their knowledge and expertise in the specific areas of DT, IoT and POE. Out of the ten personnel, three responses were received (Fig. 32). The findings are presented in Appendix E, Fig. 19 - Fig. 31.

c) Online Survey

Due to the low number of collected responses from the interview questionnaire, further action was required in order to conclude the findings from the literature review. An online survey was compiled containing twelve questions. The online survey was created to support the responses of the interview questions and ensure that the results received were not diluted by personnel with limited knowledge of the area. The survey was posted online between March 10th and March 24th, receiving fifteen responses (Fig. 44). The findings are presented in Appendix F, Fig. 33 - Fig. 43.

d) Roadmap for Creation of Digital Twins in Accordance with RIBA Plan of Work 2013

Interview participants were presented with Fig. 10 (Appendix C) and asked for feedback. The image shows the stages involved in a Level 2 BIM project and the development of a DT. The roadmap is based on a combination of factors presented in Table 2, Table 4 and Table 7 (Appendix B).

IV Interview and Survey Results

Individual responses to the interviews and online survey are presented in Appendix E and Appendix F. To add weight to the interview results, a number of survey questions were aligned to the interview questions. These instances are clearly identified. Individual graphs relating to each question are located in Appendix E and Appendix F.

a) Interview Results

From the results displayed in Fig. 19, the roadmap was deemed incomplete with 67% of participants choosing to provide supplementary information (Q1; Fig. 19 & Fig. 20). It was highlighted in the returned questionnaire form that feedback loops were not included to enable learning throughout the project. The creation of the AIM was also identified as inaccurate as the metadata required to maintain the AIM should be generated from project outset. The roadmap was entirely focused on BIM and did not account for other technologies used in the creation of digital twins. The majority of responders (66%) identified Stage 0 Strategic Definition as the desired location to introduce DT to a project, while Stage 5 was identified by one participant. This variation in appropriate stage identification eludes to uncertainty relating to the timing of technology introduction within projects (Q2; Fig. 21). All participants agreed that DT could improve BPE (Q3; Fig. 22). Three alternative answers were presented relating to penalty clauses for underperforming buildings (Q4; Fig. 23). The majority of responders (67%) rejected the proposal that DT could be used as an aid to increase collaboration on a project (Q5; Fig. 24). Three alternative answers were presented relating to DT enhancing information exchange at the project handover (Q6; Fig. 25). All participants were familiar with SL (Q7; Fig. 26). Indeed, although all participants were familiar with SL, the majority (67%) had little to no knowledge of projects providing SL (Q8; Fig. 27). All participants were familiar with COBie (Q9; Fig. 28). Although all participants were familiar with COBie, there were three alternative answers for the number of projects providing COBie. One participant reported an increase in projects requesting COBie (Q10; Fig. 29). While all participants agreed that DT can improve the handover process, it was highlighted that technology that is able to verify and validate data throughout the design process could lead to a vast improvement in the handover process (Q11; Fig. 30). The majority of responders (67%) stated that the AIM is updated occasionally after handover (Q12; Fig. 31).

b) Areas for Future Research

Blockchain is an emerging technology that has been identified as a potential solution for tying penalty clauses into the DT through a digital contract. This is an area identified by the author for future research.

Once the project has been handed over, the AIM is out of date as it does not reflect built conditions. The ability to update the AIM through DT has been identified as another area requiring further research.

c) Online Survey

All participants used BIM or intended to use BIM in the future (Q1; Fig. 33). The majority (87%) of responders use Autodesk Revit as the main source of BIM software (Q2; Fig. 34). The majority (47%) of responders identified a lack of trained operators as the main barrier to implementing BIM, followed by cost at 33% (Q3; Fig. 35). The majority (67%) of responders felt the costs of implementing BIM outweighed the financial gain (Q4; Fig. 36). Question 5 was designed to identify the main values of BIM. The majority (53%) of responders identified multi-discipline collaboration as a key value of BIM. This question was designed to identify if a participant identified the main Level 2 BIM deliverables, "Graphical and Non-graphical documentation" as an answer, which received no response (Q5; Fig. 37). The majority (53%) of responders were 60-80% satisfied with BIM (Q6; Fig. 38). 46% stated "other" in relation to BIM standards used in their office. This question was designed to identify if the participant had knowledge of standards and publications relating to Construction Operations Building Information Exchange (COBie) and Soft Landings (SL). No respondents identified either of these options, which is in accordance with interview questions 7 to 10 relating to COBie and SL (Q7; Fig. 39), supplementary information relating to Q7 is listed in Fig. 40. Approximately 37% were not familiar with any of the technologies listed and stated "none of the above". 27% of responders were familiar with Digital Twin (DT) and Internet of Things (IoT), followed by Product Data Templates (PDT) at 9% suggesting the importance of open data has not yet been acknowledged (Q8; Fig. 41). All participants agreed that the replacement of traditional information exchanges with digital information exchanges can improve the handover process. This result supports the findings from interview question 11 (Q9; Fig. 42). The majority (87%) of responders agreed that the integration of sensor technology could improve the accuracy of Building Performance Evaluation (BPE) analysis. This result also supports the findings from interview question 3 (Q10; Fig. 43).

V Discussion

a) Visualisation of Post-occupancy Evaluation (POE) Data

Although SL is a requirement of Level 2 BIM projects, the results show that although all participants were familiar with SL (Q7; Fig. 26). the number of projects providing SL information was between 0 to 20% (Q8; Fig. 27). One of the interview participants suggested that the reason SL was not implemented in current projects was due to limitations of technology for processing and visualisation of SL data gathered during POE in a meaningful way.

This same issue was identified as a problem relating to POE and BIM in a study undertaken by Goçer et al. [67]. The study proposed combining both types of data sets and presenting data through Geographic Information System (GIS) technology as a viable solution. Data was collected via onsite surveys, questionnaires and in situ-measurements relating to occupant's comfort levels, satisfaction levels, indoor environmental quality and level of perceived performance. Visualisation of building performance data was achieved by the creation of floor plans containing different layers and colour codes to represent performance conditions. Results proved that it was possible to link performance data with spatial BIM geometry and improve POE data management [67].

As a direct response to interview feedback and inspired by the work of Goçer et al. [67], a test project was created using Autodesk Revit, Dynamo and Excel. Data relating to room occupancy levels was input to Excel, and as the room occupancy levels adjusted, shading was applied to the rooms by the creation of a live link with Dynamo. The workflow for this process is outlined in Appendix F and shows that it is possible to represent POE occupancy data in Autodesk Revit and online using Microsoft Power BI to visualise and analyse real-time data.

b) Integrated BIM

The creation of common data through PDT, and the use of a common environment to store, check and validate data is essential for successful BIM projects, and is referred to as "Integrated BIM" [26]. The creation of a Common Data Environment (CDE) is a requirement of BIM Level 2 projects and is often referred to as the "single source of truth", a database of current documentation and data. The technology now exists to create an online database where data relating to multi-discipline model elements is instantly accessible to project members. Introduction of digital technology at the concept design stage will ensure that all data and metadata is fed directly into the AIM prior to project handover, resulting in an improvement in co-ordinated documentation, and reducing the level of fragmentation between disciplines and software applications.

Automation of data acquisition is possible through the digitisation of production systems. However, fully automated systems are still not in use by small and medium sized enterprises (SME) leading to traditional methods dominating data collection, which may be inaccurate and error-prone [68].

c) Bi-Directional Updating of Data

To create DT, the digital version must represent the physical version in all aspects. To ensure that the two elements remain in sync, bi-directional updating of data is required in the digital version to reflect changes made to the physical version. A current Level 2 BIM requirement is the delivery of COBie data at specified stages throughout the project. COBie is delivered via an Excel spreadsheet containing data relating to elements contained in the model at the time of extraction. Once the data contained in the Excel file is extracted from the model, it is out of-date, as it is a snapshot of the model at that point in time, and therefore it does not reflect current conditions.

It was reported by O'Sullivan and Behan [42] that COBie data was not included in over 70% of cases surveyed, while interview results show that although all participants are familiar with COBie (Fig. 28), the number of projects delivering COBie was between 20% and 40% (Fig. 29). With such a high level of awareness of COBie, but a low percentage of projects delivering COBie, future research is required to determine if COBie should remain a requirement for future Level 2 or 3 BIM projects, as it cannot feed DT with the bi-directional data updating required to remain a digital twin of a physical element.

VI Conclusion

BIM is often termed a “disruptive technology”. This is not a negative accusation however, as the disruption merely relates to the replacement of traditional methods with cutting edge digital technologies such as BIM, DT and IoT. Digital technologies have the potential to enhance all aspects of everyday life by assisting in everyday tasks and adapting and responding to the surrounding environment. The ever-increasing need and reliance on digital technologies has led to an immense improvement in the quality of wireless components such as Radio Frequency Identification Device (RFID) sensors and antennae. This in turn has led to an increase in the production of wireless components, resulting in greater variety and a reduction in cost for the consumer [11].. This is welcoming news for the construction industry, as the creation of Smart Buildings through an interconnected network of sensors is now a more viable option than ever before. The creation of a cognitive environment within a network of inter-connected buildings can lead to the digitisation of the construction industry and improve the findings of the McKinsey Report [1]. Findings have shown that integrated building sensors can warn against issues such as health concerns, increased levels of carbon monoxide, while reducing operational costs. Real-time data feed ensures that unused areas of buildings can be scheduled to shut down through recording occupational data from motion sensors, leading to an increase in the performance of new and existing buildings.

Smart technologies and smart buildings have the potential to improve the health and performance of buildings, but in order to create smart buildings, building operational data needs to be compiled that is consistent and compliant with recognised industry standards such as the BS1192 suite of documents and ISO 19650. Following the mandate of Level 2 BIM in the UK in 2016, the focus is now on Level 3 BIM and how this will affect the industry, and how best to proceed in the future. Ensuring that data generated through BIM is correctly structured and compliant with internationally recognised PDT is vital for the creation of building information data, and the subsequent creation of DT. While PAS 1192 and ISO 19650 offer guidance on best practices for the creation and sharing of digital data, users need to be rigid and ensure compliance to these standards in order to successfully transit to the next level and phase of BIM.

VII Acknowledgements

The author would like to thank Barry Kirwan, Dr. Annamarie Rogers, Lynda Keane, Dr. Avril Behan and Dr. Deborah Brennan for their support and guidance. The author also gratefully acknowledges the time and contribution given by all participants involved in the interview questionnaire and online surveys.

References

[1] J. Manyika *et al.*, "Digital America: A Tale of the Haves and Have-Mores," McKinsey Global, San Fransisco, 2015.

[2] J. K. W. Wong, J. Ge, and S. X. He, "Digitisation in facilities management: A literature review and future research directions," *Automation in Construction,* vol. 92, pp. 312-326, 2018, doi: 10.1016/j.autcon.2018.04.006.

[3] A. Bolton *et al.*, "Gemini Principles," 2018. [Online]. Available: https://www.repository.cam.ac.uk/handle/1810/284889

[4] P. Zheng, T.-J. Lin, C.-H. Chen, and X. Xu, "A systematic design approach for service innovation of smart product-service systems," *Journal of Cleaner Production,* vol. 201, pp. 657-667, 2018, doi: 10.1016/j.jclepro.2018.08.101.

[5] F. Tao, J. Cheng, Q. Qi, M. Zhang, H. Zhang, and F. Sui, "Digital twin-driven product design, manufacturing and service with big data," *The International Journal of Advanced Manufacturing Technology,* vol. 94, no. 9-12, pp. 3563-3576, 2018, doi: 10.1007/s0017.

[6] T. Uhlemann, C. Schock, C. Lehmann, S. Freiberger, and R. Steinhilper, "The Digital Twin: Demonstrating the potential of real time data acquisition in production systems," *Procedia Manufacturing,* vol. 9, pp. 113-120, 2017, doi: 10.1016/j.promfg.2017.04.043.

[7] *BS 1192:2007+A2:2016 Collaborative*

production of architectural, engineering and construction information - Code of practice., British Standards Institution, London, United Kingdom, 2016.

[8] F. H. Abanda, C. Vidalakis, A. H. Oti, and J. H. M. Tah, "A critical analysis of Building Information Modelling systems used in construction projects," *Advances in Engineering Software,* pp. 183-201, 2015, doi: 10.1016/j.advengsoft.2015.08.009.

[9] Invicara. "The platform for digital buildings." http://invicara.com/ (accessed Jan.14, 2019).

[10] Willow. "The Willow Twin." https://www.willowinc.com/products/ (accessed Jan.14, 2019).

[11] M. Xu, J. M. David, and S. H. Kim, "The Fourth Industrial Revolution: Opportunities and Challenges," *International Journal of Financial Research,* vol. 9, no. 2, pp. 90-95, 2018, doi: 10.5430/ijfr.v9n2p90.

[12] M. Gunduz, U. Isikdag, and M. Basaraner, "Integration of BIM, Web Maps and IoT for Supporting Comfort Analysis," presented at the 4th International GeoAdvances Workshop, Safranbolu, Karabuk, Turkey, 2017.

[13] K. M. Chang, R. J. Dzeng, and Y. J. Wu, "An Automated IoT Visualization BIM Platform for Decision Support in Facilities Management," *Applied Sciences,* vol. 8, no. 7, p. 1086, 2018, doi: 10.3390/app8071086.

[14] C. Z. Li, F. Xue, X. Li, J. Hong, and G. Q. Shen, "An Internet of Things-enabled BIM platform for on-site assembly services in prefabricated construction," *Automation in Construction,* vol. 89, pp. 146-161, 2018, doi: 10.1016/j.autcon.2018.01.001.

[15] Z. Pourzolfaghar, P. McDonnell, and M. Helfert, "Barriers to Benefit from Integration of Building Information with Live Data from IOT Devices during the Facility Management Phase," in *CITA BIM Gathering 2017 Proceedings*, Dublin, Ireland, 2017: CITA, pp. 213-217.

[16] M. Alves, P. Carreira, and A. A. Costa, "BIMSL: A generic approach to the integration of building information models with real-time sensor data," *Automation in Construction,* vol. 84, pp. 304-314, 2017, doi: 10.1016/j.autcon.2017.09.005.

[17] B. Dave, A. Buda, A. Nurminen, and K. Främling, "A framework for integrating BIM and IoT through open standards," *Automation in Construction,* vol. 95, pp. 35-45, 2018, doi: 10.1016/j.autcon.2018.07.022.

[18] M. Royapoor, A. Antony, and T. Roskilly, "A review of building climate and plant controls, and a survey of industry perspectives," *Energy and Buildings,* vol. 158, pp. 453-465, 2018, doi: 10.1016/j.enbuild.2017.10.022.

[19] M. Enzer *et al.* "Roadmap for delivering the information management framework for the built environment." Centre for Digital Built Britain. https://www.cdbb.cam.ac.uk/ (accessed Apr.19, 2019).

[20] National Infrastructure Commission, "Data for the public good," 2017. [Online]. Available: https://www.nic.org.uk/wp-content/uploads/Data-for-the-Public-Good-NIC-Report.pdf

[21] Y. Arayici, T. Fernando, V. Munoz, and M. Bassanino, "Interoperability specification development for integrated BIM use in performance based design," *Automation in Construction,* vol. 85, pp. 167–181, 2018, doi: 10.1016/j.autcon.2017.10.018.

[22] *PAS1192-5:2015 Specification for security-minded building information modelling, digital built environments and smart asset management*, British Standards Institution, London, United Kingdom, 2015.

[23] Y.-C. Lee, C. M. Eastman, and W. Solihin, "Logic for ensuring the data exchange integrity of building information models," *Automation in Construction,* vol. 85, pp. 249–262, 2018, doi: 10.1016/j.autcon.2017.08.010.

[24] B. D. Baron. "How UCSF Health is putting patients first with facilities management." https://www.ibm.com/blogs/internet-of-things/iot-ucsf-health-and-maximo-smart-medical-buildings/ (accessed Jan.02, 2019).

[25] M. Kaseem, G. Kelly, N. Dawood, M. Serginson, and S. Lockley, "BIM in facilities management applications: a case study of a large university complex," *Built Environment Project and Asset Management,* vol. 5, no. 3, pp. 261-277, 2015, doi: 10.1108/BEPAM-02-2014-0011.

[26] A. Mecheri and R. P. West, "Breaking into the black box - Demystifying BIM data," in *CITA BIM Gathering 2017*, Dublin, Ireland, 2017, pp. 9-14.

[27] A. Andriamamonjy, D. Saelens, and R. Klein, "An automated IFC-based workflow for building energy performance simulation with Modelica," *Automation in Construction,* vol. 91, pp. 166–181, 2018, doi: 10.1016/j.autcon.2018.03.019.

[28] *Building construction — Organization of information about construction works — Part 2: Framework for classification*, International Organization for Standardization, Switzerland, 2015.

[29] *Industry Foundation Classes (IFC) for data sharing in the construction and facility management industries*, International Organization for Standardization, Switzerland, 2013.

[30] European Commision. "Construction products (CPD/CPR) - Internal Market, Industry, Entrepreneurship and SMEs." https://ec.europa.eu/growth/single-market/european-standards/harmonised-standards/construction-products_en (accessed Jan. 18, 2019).

[31] E. Schulze. "Product Data Templates based on CEN/CENELEC standards, stored in a European data dictionary framework." http://m.trevare.no/getfile.php/Filer/EspenSchulze%20CEN.pptx2.pdf (accessed Jan.03, 2019).

[32] K. Farghaly, H. F. Abanda, C. Vidalakis, and G. Wood, "Taxonomy for BIM and Asset Management Semantic Interoperability," *Journal of Management in Engineering,* vol. 34, no. 4, pp. 1-34, 2018, doi: 10.1061/(ASCE)ME.1943-5479.0000610.

[33] Building Research Establishment. "DataBook for construction - The new BIM data library." Building Research Establishment Ltd. https://bregroup.com/expertise/bim/about-databook/ (accessed Jan.18, 2019).

[34] Co Builder. "Standardise your product data with goBIM." coBuilder UK. https://cobuilder.com/en/gobim/ (accessed Feb. 27, 2019).

[35] *Asset management - Overview, principles and terminology*, British Standards Institution, Switzerland, 2014.

[36] *PAS 1192:2 2013 - Specification for information management for the capital/delivery phase of construction projects using building information modelling*, British Standards Institution, London, United Kingdom, 2013.

[37] British Standards Institution. "About BIM Level 2." https://bim-level2.org/ (accessed Jan.10, 2019).

[38] *BS EN ISO 19650-1:2018. Organization and digitization of information about buildings and civil engineering works, including building information modelling (BIM). Information management using building information modelling. Concepts and principles*, British Standards Institution, 2019.

[39] *BS1192-4:2014 - Collaborative production of information Part 4 - Fulfilling employer's information exchange requirements using COBie - Code of practice*, British Standards Institution, London, United Kingdom, 2014.

[40] B. East. "Construction-Operations Building Information Exchange (COBie)." Whole Building Design Guide. http://www.wbdg.org/resources/construction-operations-building-information-exchange-cobie (accessed Jan.06, 2019).

[41] K. Kim and J. Yu, "Ontology-based Facility Maintenance Information Integration Model using IFC-based BIM data," in *The 6th International Conference on Construction Engineering and Project Management*, Busan, Korea, 2015, pp. 280-283.

[42] P. O'Sullivan and A. Behan, "What Lessons Can Be Learned From The Delivery Of The First Building On The Grangegorman Campus Using Building Information Management (BIM)?," in *CitA BIM Gathering 2017 Proceedings*, Dublin, Ireland, 2017, pp. 92-100.

[43] Royal Institute of British Architects, *Guide to using the RIBA Plan of Work 2013*. London, United Kingdom: RIBA Publishing, 2013.

[44] P. Fletcher and H. Satchwell, "RIBA Stage Guides Briefing A Practical Guide to RIBA Plan of Work 2013 Stages 7, 0 and 1," RIBA, London, 2015.

[45] T. Bailey, "RIBA Stage Guides Design A Practical Guide to RIBA Plan of Work 2013 Stages 2 and 3," RIBA London, 2015.

[46] P. Holden, "RIBA Stage Guides Construction A Practical Guide to RIBA Plan of Work 2013 Stages 4, 5 and 6," RIBA, London, 2015.

[47] T. Jarvinen, "Virtual Reality Models in Cleanroom Design," in *49th R3 Nordic Symposium. Cleanroom Technology, Contamination Control and Cleaning. Proceedings*, Naantali, Finland, 2018, pp. 11-16.

[48] B. McAuley, A. Hore, and R. P. West, "Developing Key Performance Indicators to Measure the Effectiveness of Early Facilities Management Performance on BIM Governed Public Sector Projects," *CITA BIM Gathering,* pp. 198-206, 2015.

[49] *BG 54/2014 the Soft Landings Framework for better briefing, design, handover and*

building performance in-use, Building Services Research and Information Association, 2014.

[50] *BG 54/2018 Soft Landings Framework 2018 Six Phases for Better Buildings*, Building Services Research and Information Association, 2018.

[51] *BG 61/2015 Soft Landings & Government Soft Landings. A Convergence Guide for Construction Projects*, Building Services Research and Information Association, 2015.

[52] Building Services Research and Information Association. "Sustainable Construction case study - University of East Anglia." https://www.bsria.co.uk/news/article/sustainable-construction-case-study-university-of-east-anglia/ (accessed Jan. 02, 2019).

[53] *BG 63/2015 Building Performance Evaluation in Non-Domestic Buildings*, Building Services Research and Information Association, 2015.

[54] D. Lee, G. Cha, and S. Park, "A study on data visualization of embedded sensors for building energy monitoring using BIM," *International Journal of Precision Engineering and Manufacturing,* vol. 17, no. 6, pp. 807-814, 2016, doi: 10.1007/s12541-016-0099-4.

[55] Presidion. "Case Study – Tesco Ireland." https://www.presidion.com/case-study-tesco-ireland/ (accessed Jan. 01, 2019).

[56] M. F. I. C. Ros, Z. Ismail, and F. Hassan, "Establishing key elements for sustainable PFI projects: A critical literature review," in *2012 IEEE Symposium on Business, Engineering and Industrial Applications*, Bandung, 2012, pp. 658-663, doi: 10.1109/ISBEIA.2012.6422971.

[57] Building Research Establishment. "Central Bank of Ireland." Building Research Establishment Ltd. https://www.breeam.com/case-studies/offices/central-bank-of-ireland/ (accessed Jan.15, 2019).

[58] Y. Lu, Z. Wu, R. Chang, and Y. Li, "Building Information Modeling (BIM) for green buildings: A critical review and future directions," *Automation in Construction,* vol. 83, pp. 134–148, 2017, doi: 10.1016/j.autcon.2017.08.024.

[59] F. Jalaei and A. Jrade, "Integrating building information modeling (BIM) and LEED system at the conceptual design stage of sustainable buildings," *Sustainable Cities and Society,* vol. 18, pp. 95-107, 2015, doi: doi.org/10.1016/j.scs.2015.06.007.

[60] K. Kim, H. Kim, W. Kim, C. Kim, J. Kim, and J. Yu, "Integration of ifc objects and facility management work information using Semantic Web," *Automation in Construction,* vol. 87, pp. 173-187, 2018, doi: 10.1016/j.autcon.2017.12.019.

[61] J. Teizer *et al.*, "Internet of Things (IoT) for Integrating Environmental and Localization Data in Building Information Modeling (BIM)," in *34th International Symposium on Automation and Robotics in Construction*, Taiwan, 2017.

[62] A. L. C. Ciribini *et al.*, "Tracking users' behaviors through real-time information in BIMs: Workflow for interconnection in the Brescia Smart Campus Demonstrator," *Procedia Engineering,* vol. 180, pp. 1484 – 1494, 2017, doi: 10.1016/j.proeng.2017.04.311.

[63] S. Breslav. "Using Forge for Advanced IoT Visualization in Dasher 360." https://www.autodesk.com/autodesk-university/class/Using-Forge-Advanced-IoT-Visualization-Dasher-360-2017 (accessed Jan. 02, 2019).

[64] A. R. Hevner, S. T. March, J. Park, and S. Ram, "Design science in information systems research," *MIS Quarterly,* vol. 28, no. 1, pp. 75-105, 2004.

[65] K. Peffers, T. Tuunanen, M. A. Rothenberger, and S. Chatterjee, "A Design Science Research Methodology for Information Systems Research," *Journal of Management Information Systems,* vol. 24, no. 3, pp. 45-78, 2007.

[66] P. Offermann, O. Levina, M. Schönherr, and U. Bub, "Outline of a design science research process," presented at the Proceedings of the 4th International Conference on Design Science Research in Information Systems and Technology. DESRIST 2009, Philadelphia, Pennsylvania, USA, 2009.

[67] O. Göçer, Y. Hua, and K. Göçer, "Completing the missing link in building design process: Enhancing post-occupancy evaluation method for effective feedback for building performance," *Building and Environment,* vol. 89, pp. 14-27, 2015, doi: 10.1016/j.buildenv.2015.02.011.

[68] G. Xu, M. Li, C. H. Chen, and Y. Wei, "Cloud asset-enabled integrated IoT platform for lean prefabricated construction," *Automation in Construction,* vol. 93, pp. 123-134, 2018, doi: 10.1016/j.autcon.2018.05.012.

APPENDIX A – LEVEL 2 BIM INFORMATION DELIVERY CYCLE

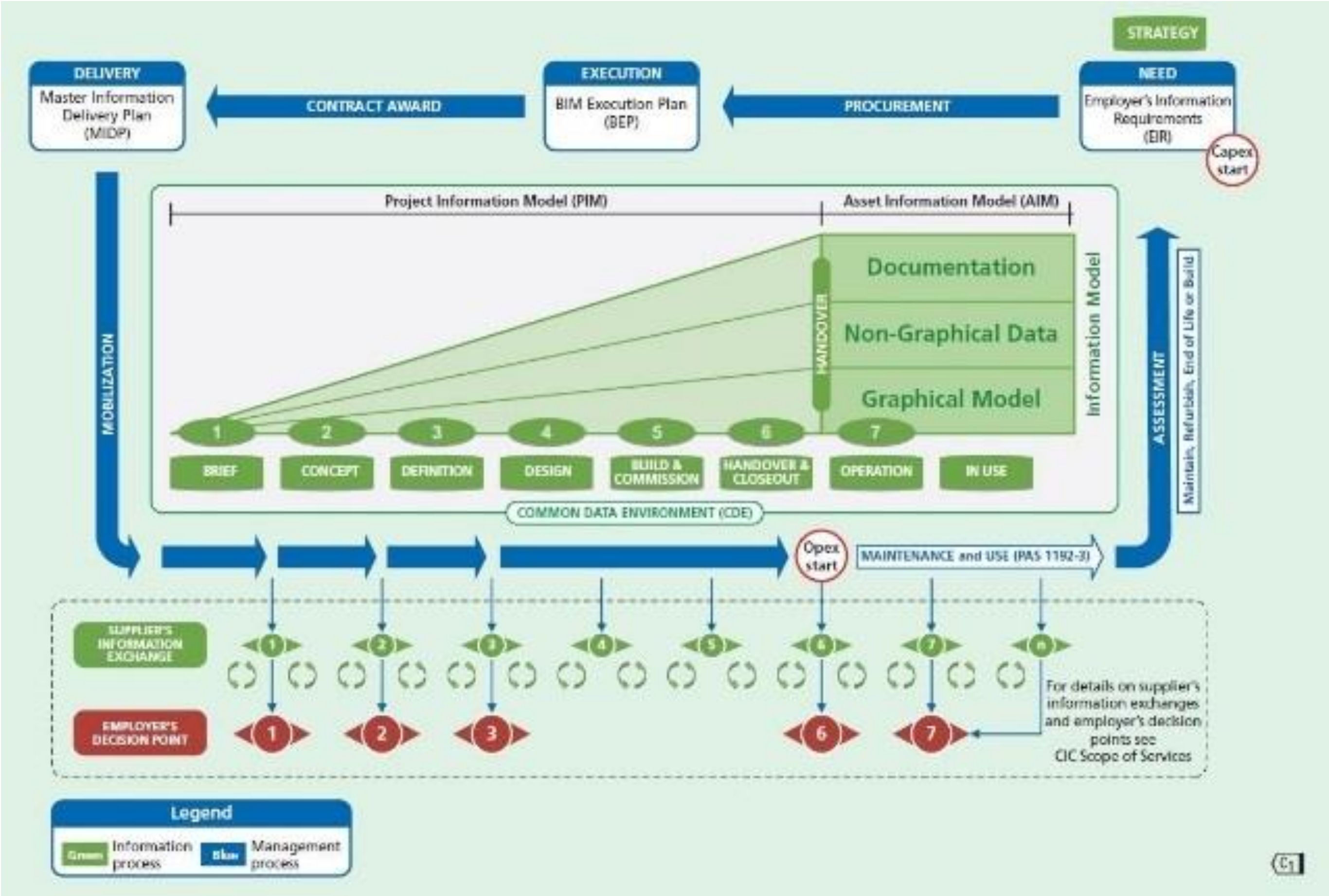


Fig. 9: PAS 1192-2:2013 Information delivery cycle [36]

Fig. 9 displays the information delivery cycle illustrates the seven stages and information exchange locations of a Level 2 BIM project. Stage 0 is not shown as no data deliverables are required at the outset of the project.

APPENDIX B – COMPARISON OF RIBA PLAN OF WORK 2013 AND SOFT LANDINGS 2018 INFORMATION DELIVERABLES

Table 7: Comparison of information deliverables

RIBA Plan of Work 2013								
Description:	Stage 0	Stage 1	Stage 2	Stage 3	Stage 4	Stage 5	Stage 6	Stage 7
	Strategic Definition	Preparation & Brief	Concept Design	Developed Design	Technical Design	Construction	Handover & Closeout	In Use
Information Exchange Requirement:	Sharing and confirming the strategic brief	Sharing and confirming the initial project brief	Concept design from each discipline	Co-ordinated architectural, structural and building services design	Technical design information	O&M file. As constructed information. Building user guide.	Federated BIM	As constructed information. Feedback on building performance.

Soft Landings 2018						
Description:	Phase 1	Phase 2	Phase 3	Phase 4	Phase 5	Phase 6
Information Exchange Requirement:	Identify all actions needed to support the procurement	Support the design as it evolves	Plan for commissioning and handover	Prepare for building readiness. Provide technical guidance	Support in the first few weeks of occupation	Monitoring review, fine-tuning and feedback

Progression of Digital Information								
Description:	Stage 0	Stage 1	Stage 2	Stage 3	Stage 4	Stage 5	Stage 6	Stage 7
Virtual:								
Physical:								
Digital Twin:								
FM:								

Table 7 displays a comparison of information deliverables between the RIBA Plan of Work 2013 stages, and the Soft Landings 2018 Framework. The progression of Digital Information transferring to the Digital Twin through information exchanges is displayed to indicated progression throughout the project.

APPENDIX C: ROADMAP FOR THE CREATION OF DIGITAL TWINS IN ACCORDANCE WITH RIBA PLAN OF WORK 2013

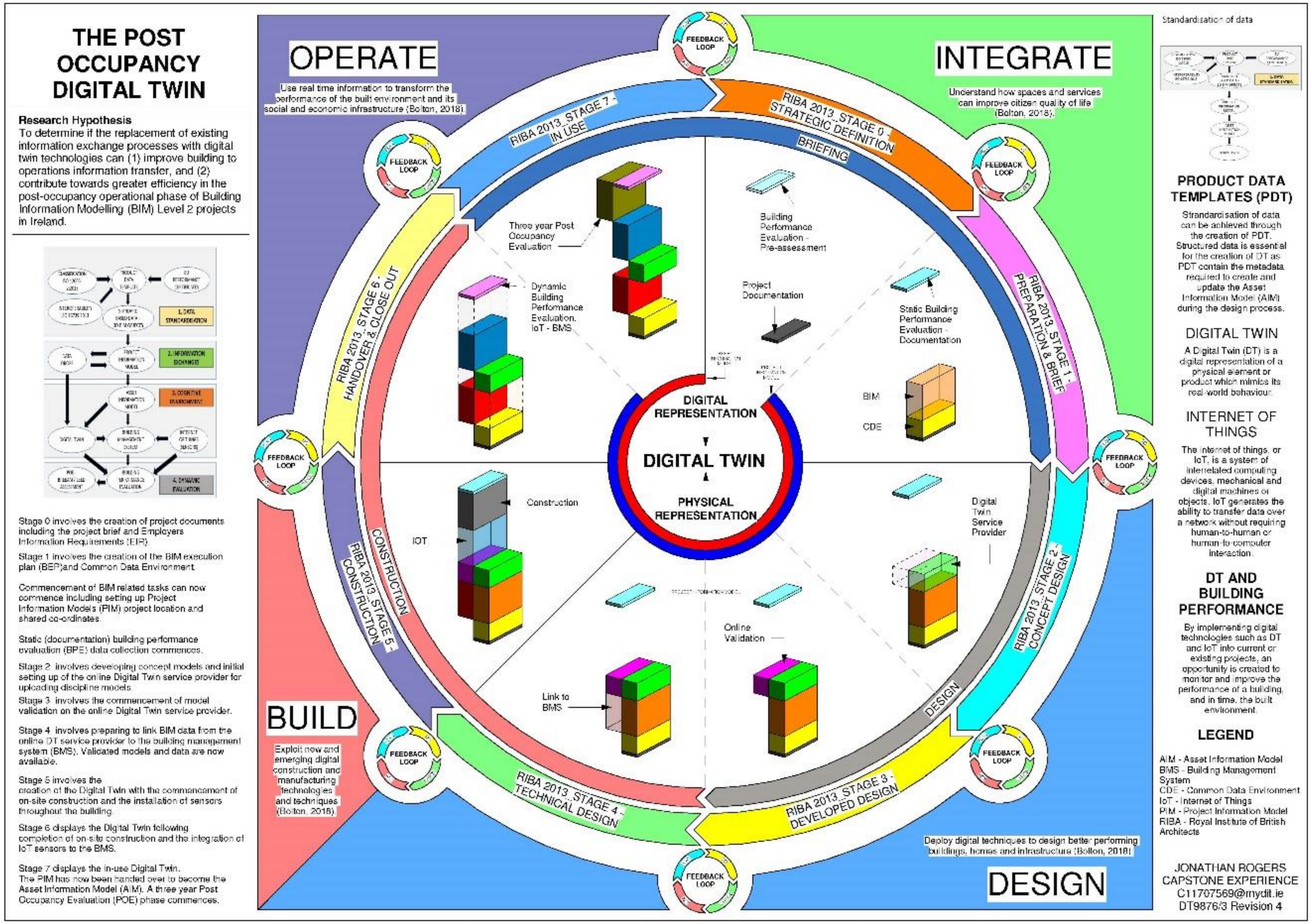


Fig. 10: Roadmap for creation of Digital Twins

Fig. 10 displays a schematic for a roadmap for the creation of Digital Twins in accordance to the information deliverables identified in the RIBA Plan of Work 2013, and Soft Landings 2018 Framework.

APPENDIX D – STAGES OF ROADMAP IN ACCORDANCE WITH RIBA PLAN OF WORK 2013

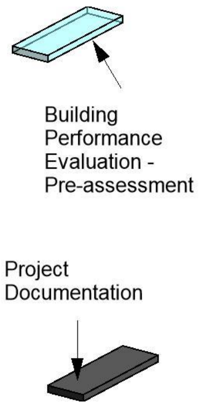


Fig.11: RIBA Plan of Work 2013 - Stage 0

Stage 0: Creation of a BIM execution plan (BEP) and Common Data Environment.

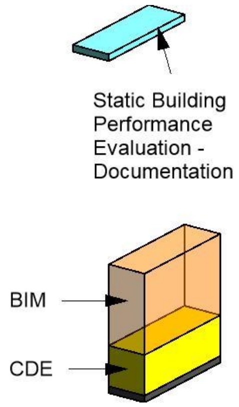


Fig. 12: RIBA Plan of Work 2013 - Stage 1

Stage 1 involves the creation of the BIM execution plan (BEP)and Common Data Environment.

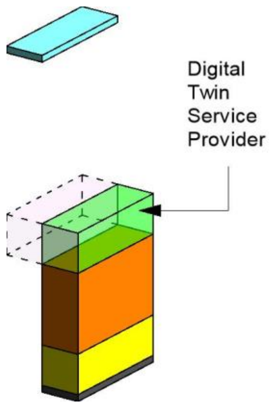


Fig. 13: RIBA Plan of Work 2013 - Stage 2

Stage 2: Development of concept models and setting up of an online Digital Twin service provider for uploading discipline models.

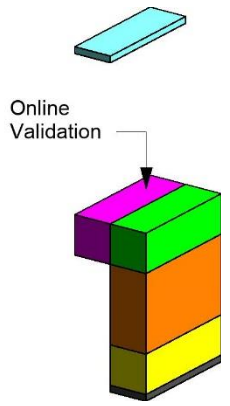


Fig. 14: RIBA Plan of Work 2013 - Stage 3

Stage 3: Commencement of model validation on the online Digital Twin service provider.

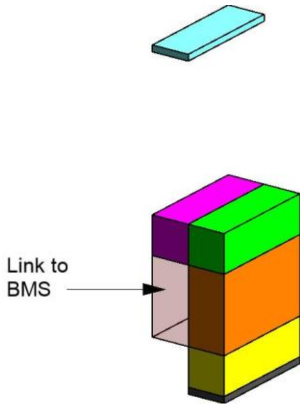


Fig. 15: RIBA Plan of Work 2013 - Stage 4

Stage 4: Preparing to link BIM data from the online DT service provider to the Building Management System (BMS). Validated models and data are now available.

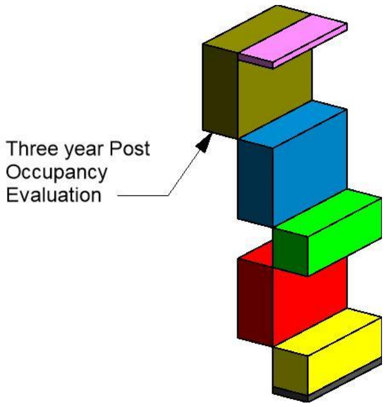


Fig. 17: RIBA Plan of Work 2013 - Stage 6

Stage 6: Display of Digital Twin following completion of on-site construction and integration of IoT sensors with the BMS.

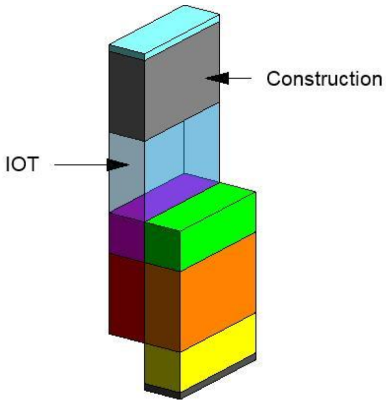


Fig. 16: RIBA Plan of Work 2013 - Stage 5

Stage 5: Creation of the Digital Twin with the commencement of on-site construction and the installation of sensors.

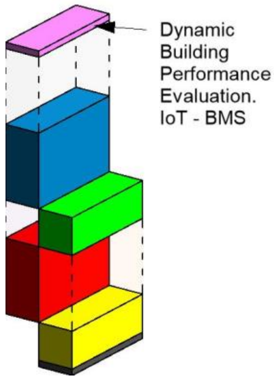


Fig. 18: RIBA Plan of Work 2013 - Stage 7

Stage 7: Display of in-use Digital Twin. The PIM has now been handed over to become the Asset Information Model (AIM). A three-year Post-occupancy Evaluation (POE) phase commences.

Appendix E – Interview Questionnaire Results

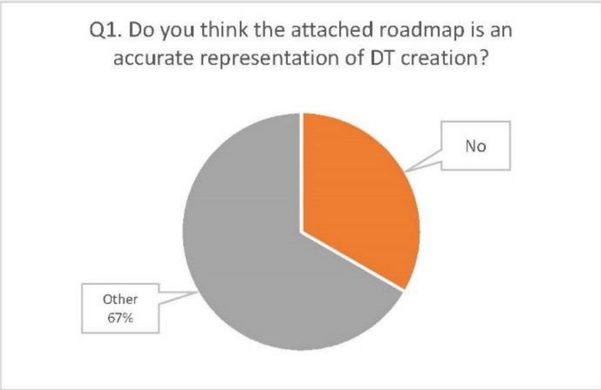


Fig. 19: Interview Results - Question 1

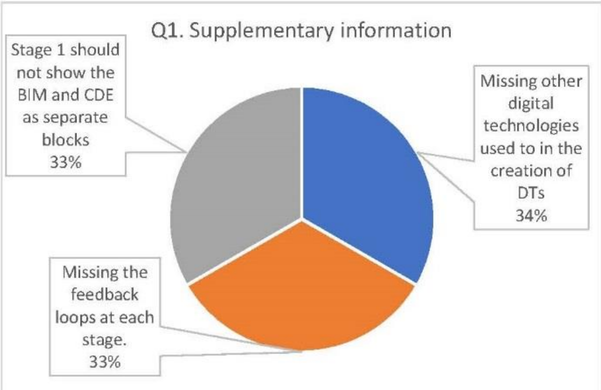


Fig. 20: Interview Results - Question 1 Supplementary Information

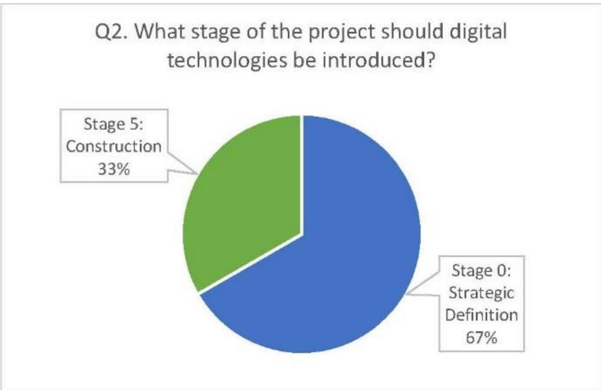


Fig. 21: Interview Results - Question 2

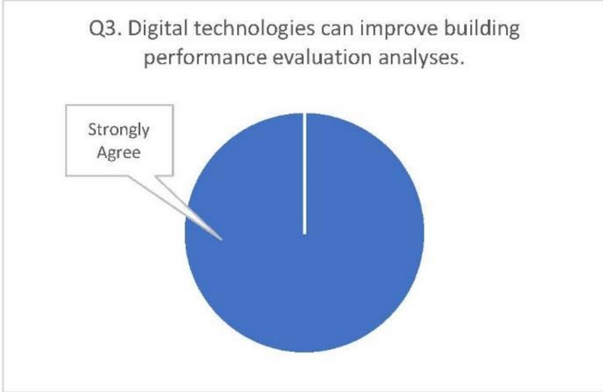


Fig. 22: Interview Results - Question 3

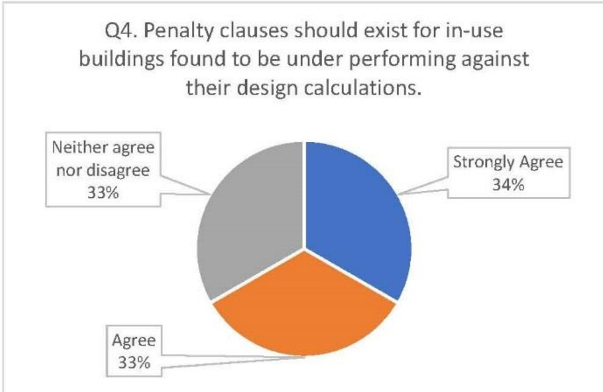


Fig. 23: Interview Results - Question 4

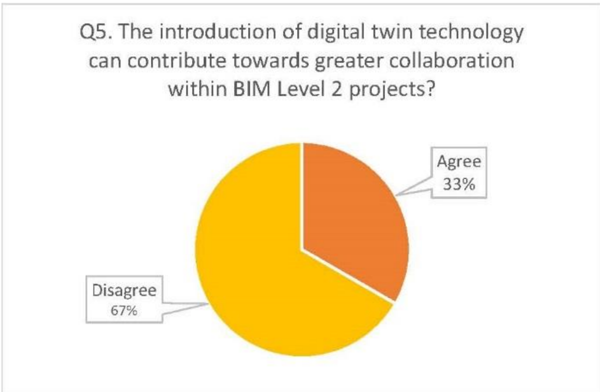


Fig. 24: Interview Results - Question 5

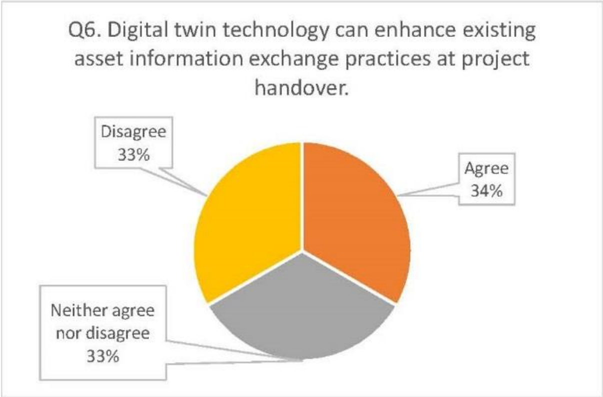


Fig. 25: Interview Results - Question 6

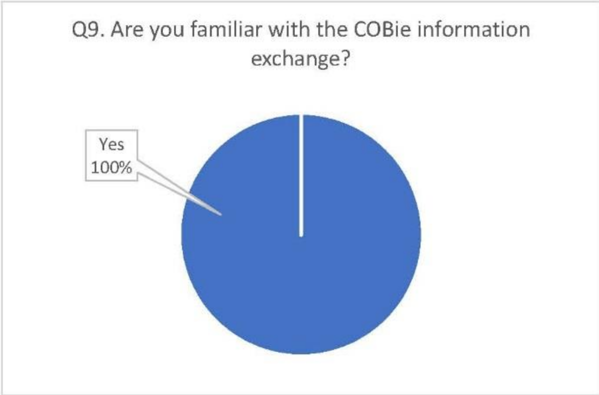


Fig. 28: Interview Results - Question 9

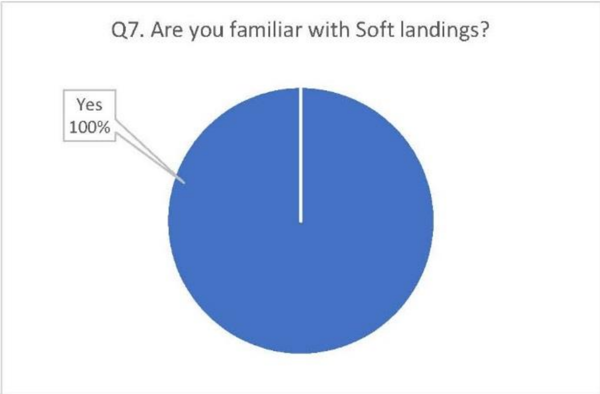


Fig. 26: Interview Results - Question 7

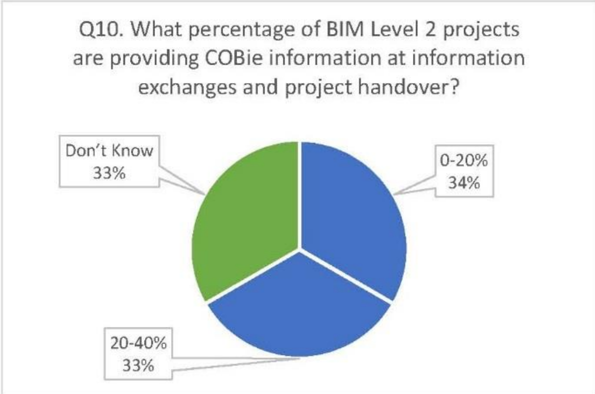


Fig. 29: Interview Results - Question 10

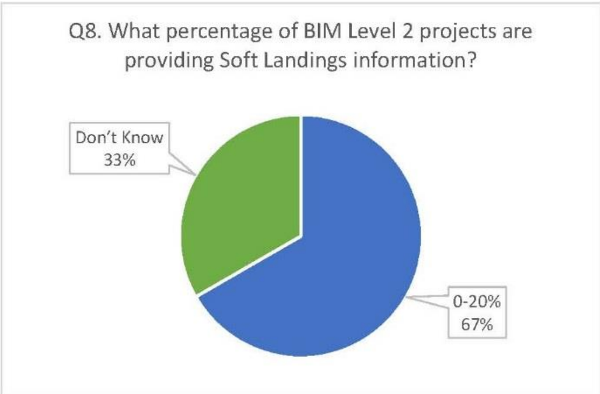


Fig. 27: Interview Results - Question 8

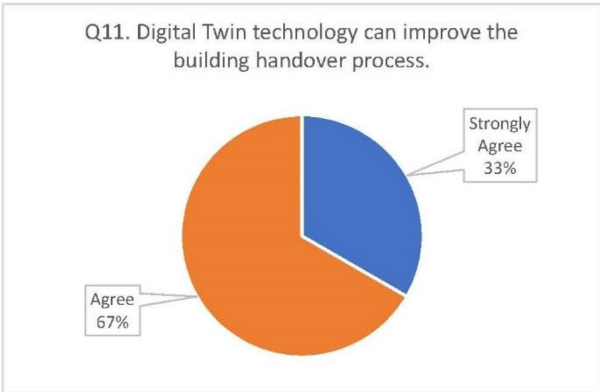


Fig. 30: Interview Results - Question 11

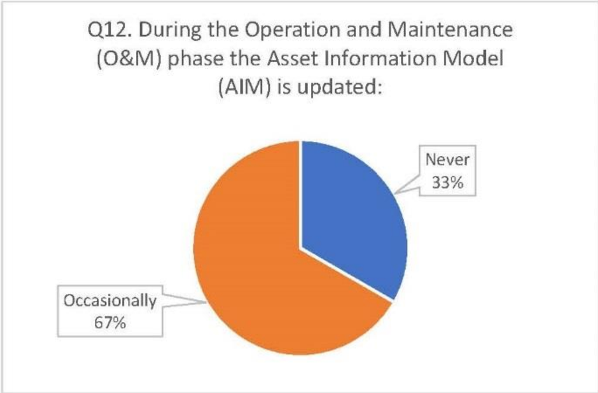


Fig. 31: Interview Results - Question 12

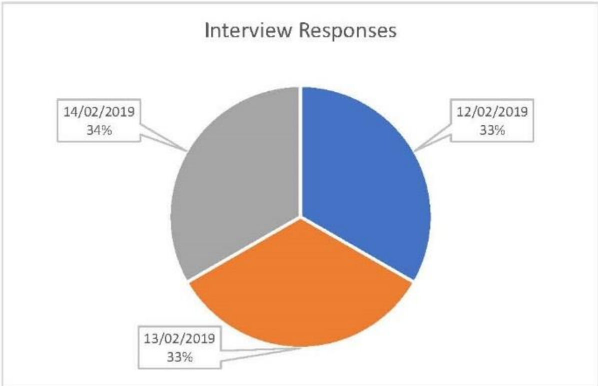


Fig. 32: Interview Responses

APPENDIX F – ONLINE SURVEY RESULTS

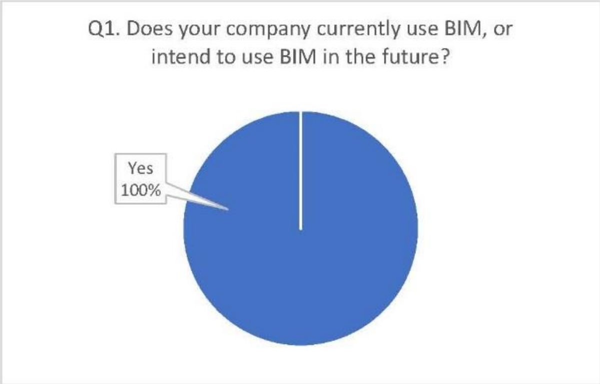


Fig. 33: Online Survey Results - Question 1

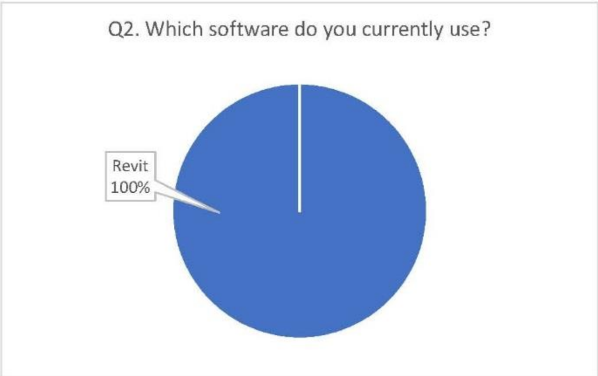


Fig. 34: Online Survey Results - Question 2

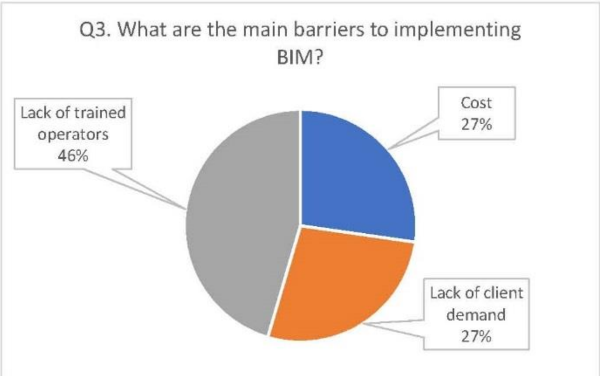


Fig. 35: Online Survey Results - Question 3

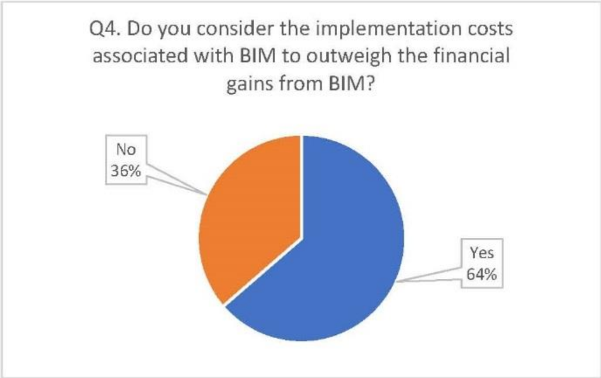


Fig. 36: Online Survey Results - Question 4

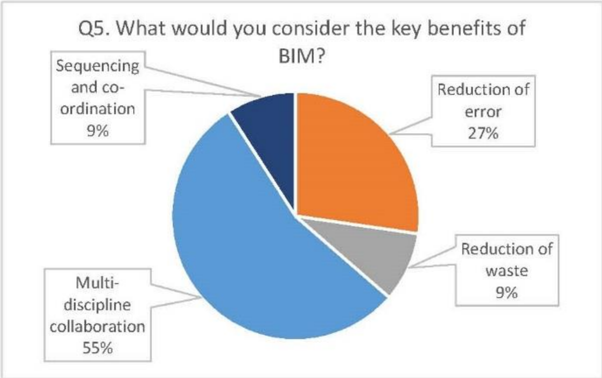


Fig. 37: Online Survey Results - Question 5

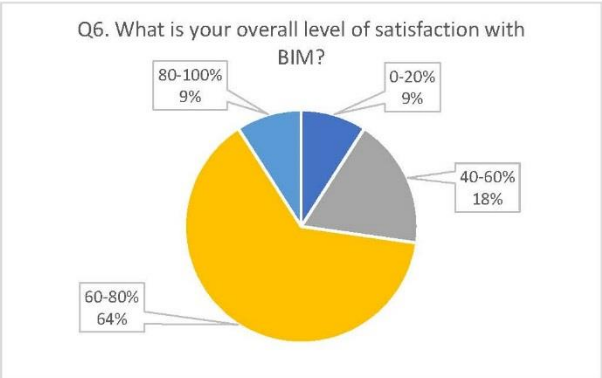


Fig. 38: Online Survey Results - Question 6

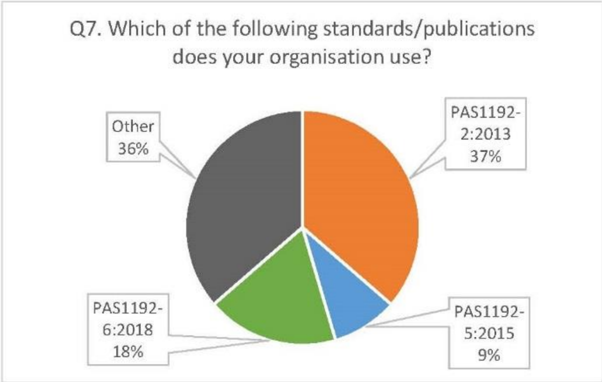


Fig. 39: Online Survey Results - Question 7

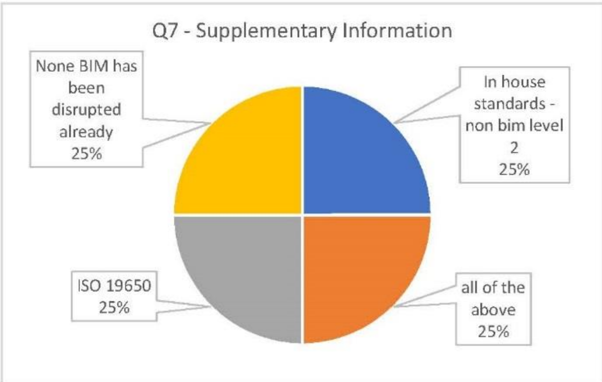


Fig. 40: Online Survey Results - Question 7 – Supplementary Information

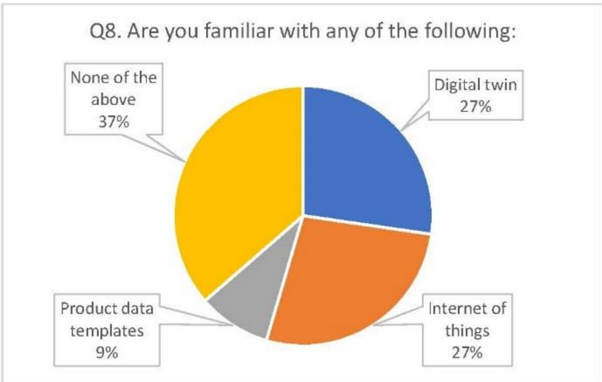


Fig. 41: Online Survey Results - Question 8

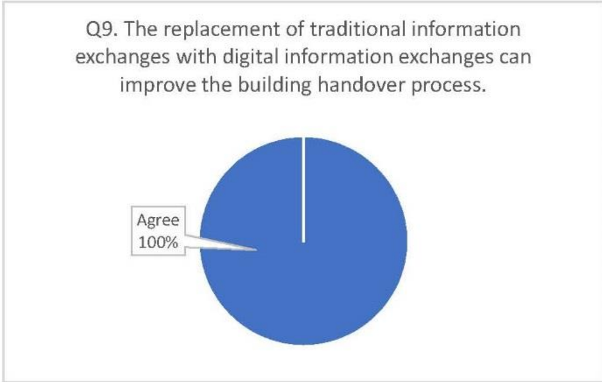


Fig. 42: Online Survey Results - Question 9

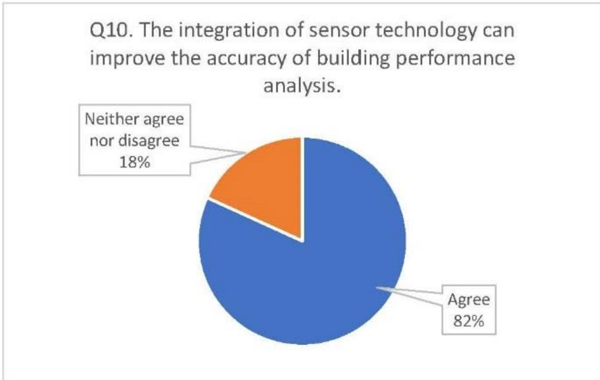


Fig. 43: Online Survey Results - Question 10

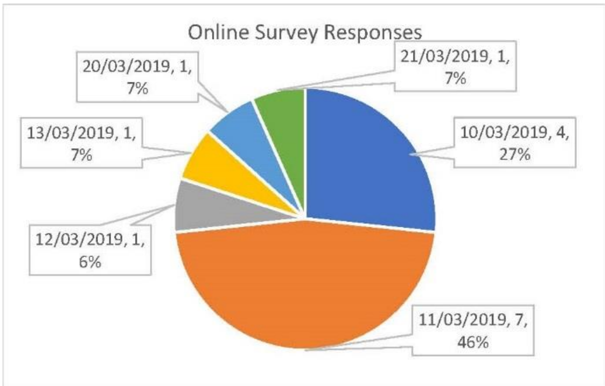


Fig. 44: Online Survey Responses

APPENDIX G – POST-OCCUPANCY EVALUATION - DATA VISUALISATION WORKFLOW

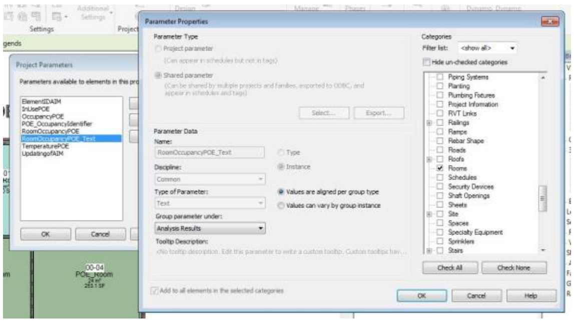
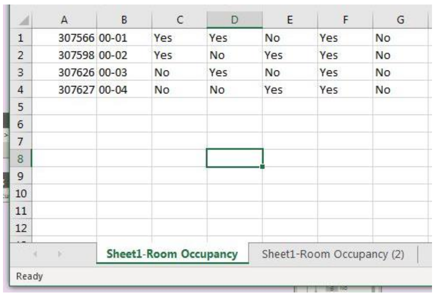


Fig. 45: POE Project Parameters

Creation of Room Occupancy Shared Parameter and assigning to Room category



	A	B	C	D	E	F	G
1	307566	00-01	Yes	Yes	No	Yes	No
2	307598	00-02	Yes	No	Yes	Yes	No
3	307626	00-03	No	Yes	No	Yes	No
4	307627	00-04	No	No	Yes	Yes	No

Fig. 48: Occupancy Data in Excel

Excel sheet displaying Revit ID, Room Number and Occupancy data

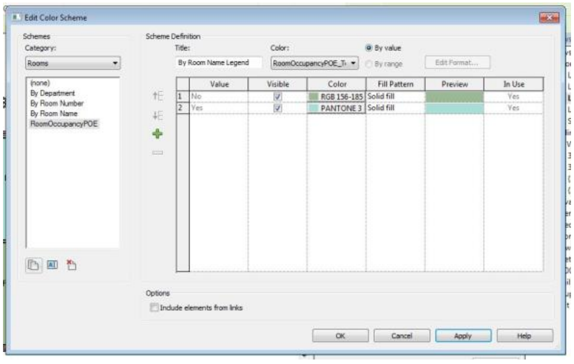


Fig. 46: POE Occupancy Colour Scheme

New colour scheme based on Room Occupancy Shared Parameter

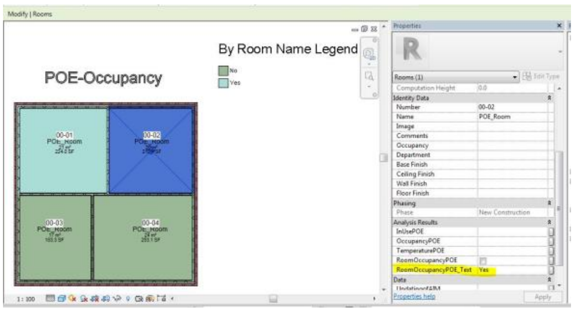


Fig. 49: Parameter Reading Excel Data

Example of a typical Revit room with data assigned to the Instance Parameter to activate filter

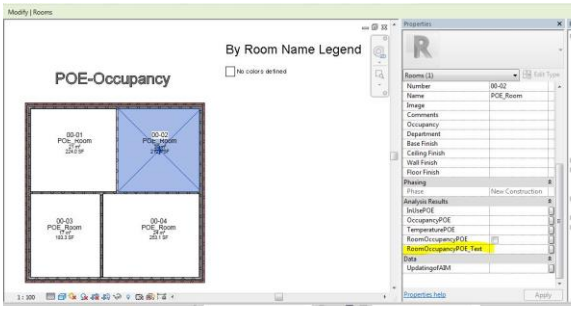


Fig. 47: Parameter Assigned to Room

Example of a typical Revit room before data is assigned to the Instance Parameter

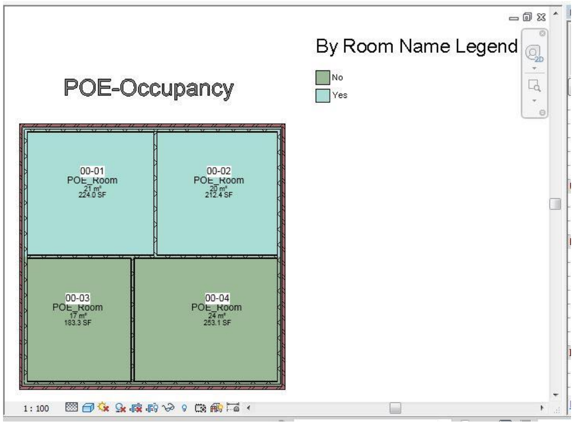


Fig. 50: Room Occupancy Data - Option A

See Excel data in column C (Fig. 48).

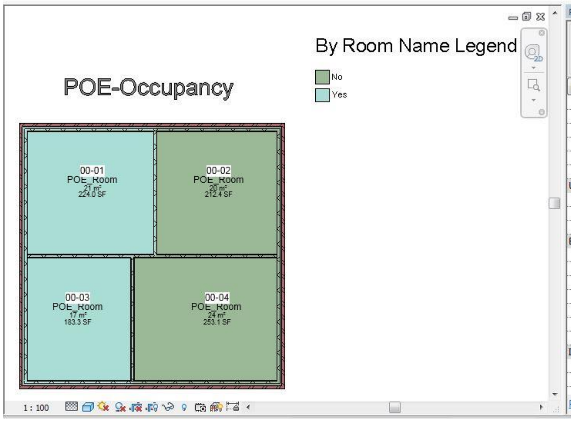


Fig. 51: Room Occupancy Data – Option B

See Excel data in column D (Fig. 48).

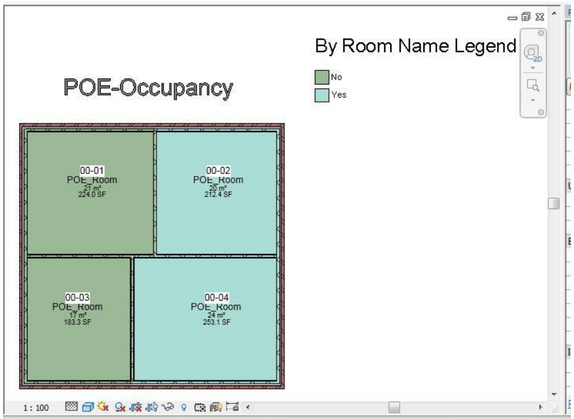


Fig. 52: Room Occupancy Data – Option C

See Excel data in column E (Fig. 48).

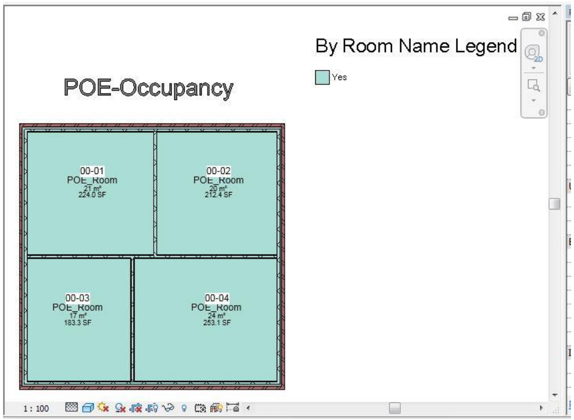


Fig. 53: Room Occupancy Data – Option D

See Excel data in column F (Fig. 48).

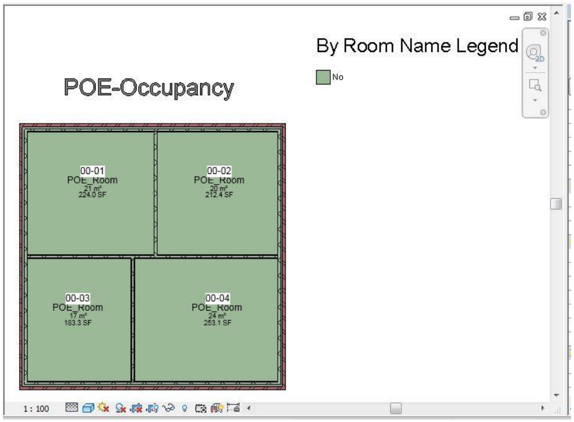


Fig. 54: Room Occupancy Data – Option E

See Excel data in column G (Fig. 48).

a) Dynamo Script Number 3: Writing Room ID's and Room Number to Excel

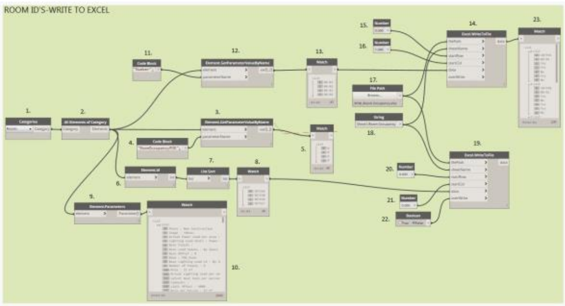


Fig. 55: Room ID's – Write to Excel

Dynamo script number 3: Writing Room ID's and Room Number to Excel. Dynamo script number 1 nodes and values. See red notebook – Page 84

1. Categories (Rooms)
2. All elements of category
3. Element.GetParameterValueByName
4. CodeBlock (RoomOccupancyPOE)
5. Watch
6. Element.ID
7. List.Sort
8. Watch
9. Element.Parameters
10. Watch
11. CodeBlock (Number)
12. Element.GetParameterValueByName
13. Watch
14. Excel.WriteToFile
15. Number (0)
16. Number (1)
17. FilePath
18. String (Sheet1-Room Occupancy)
19. Excel.WriteToFile
20. Number (0)
21. Number (1)
22. Boolean (False)
23. Watch

d) Dynamo Script Number 4: Reading room occupancy data from Excel

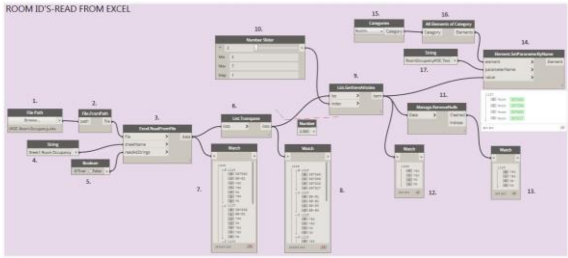


Fig. 56: Room ID's – Read from Excel

Dynamo script number 4: Reading room occupancy data from Excel. Dynamo script number 2 nodes and values. See red notebook – Page 85

1. FilePath
2. File.FromPath
3. Excel. ReadFromFile
4. String (Sheet1-Room Occupancy)
5. Boolean (True)
6. List.Transpose
7. Watch
8. Watch
9. List.GetItemsAtIndex
10. Number Slider
11. Manage.RemoveNulls
12. Watch
13. Watch
14. Element.SetParameterByName
15. Categories (Rooms)
16. All elements of category
17. String (Room OccupancyPOE-Text)