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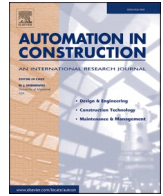Fang, Zigeng; Liu, Yan; Lu, Qiuchen; Pitt, Michael; Hanna, Sean; Tian, Zhichao

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BIM-integrated portfolio-based strategic asset data quality management

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ABSTRACT

A building's strategic asset management (SAM) capability has traditionally been limited by its site-based management. With the emergence of needs from clients about delivering a long-term portfolio-based building asset management plan that minimizes the asset risk and optimizes the value of their asset portfolios, SAM Units have emerged as a new business form to provide various SAM services to their clients. However, the quality of their current data model is still hindered by many issues, such as missing important attributes and the lack of customized information flow guidance. In addition, there is a gap in integrating their existing data collection with various data sources and Building Information Modeling (BIM) to enhance their data quality. By evaluating a SAM Unit's portfolio case study, this paper identifies the factors limiting the quality of SAM Units' data model and develops a guide to integrating various data sources better. We develop a BIM-integrated portfolio-based SAM information flow framework and a detailed hierarchical portfolio-based non-geometric data structure. The proposed framework and data structure will help SAM professionals, building asset owners, and other facilities management professionals embrace the benefits of managing the portfolio-based SAM data.

1. Introduction

By adopting digital tools like Building Information Modeling (BIM), practitioners can up-scale building information's consistency, computability, and coordinate capability in the construction industry to the next level [1]. However, BIM research has mainly leaned towards the design and construction phases, not the operations and maintenance phase [2], even though one of the major aims of BIM is to integrate information throughout the whole building lifecycle. Only a few studies look into the processes and information requirements of how BIM can be successfully implemented in operations and maintenance [1–3].

In the O&M (Operation and Maintenance) phase, to better utilize the previously developed information from the design and construction phases, professionals need to know what information is needed and how precisely it is needed to be built in BIM models. However, in reality, these requirements are hardly confirmed and agreed upon for the following reasons: 1) There are no widely accepted guidelines or agreements over the necessary information and format for the BIM applications in the O&M phase [1,4]. 2) The involvement of the O&M professionals in the design and construction phases is limited due to the

unrevealed value of integrated asset management information handover [5]. 3) Nearly all construction projects are unique in their own way, which makes the predictions about their asset information completeness level difficult and imprecise (e.g., different design and construction methods, environmental changes, building types, operational manners, and occupants) [6]. As such, O&M professionals end up taking the design and construction project information left after the project handover process to support their O&M tasks. Unfortunately, it is noticed that the data collected and constructed by these different stakeholders (e.g., architects, contractors, and manufacturers) and methodologies are heterogeneous [7]. In general, studies over how and whether building asset information in the design and construction phases is used in O&M practices are limited [8].

In the context of this study, we borrow the definition from ISO 55000 for Strategic Asset Management Plan (SAMP), which is "Strategic Asset Management Plan: documented information that specifies how organizational objectives are to be converted into asset management objectives, the approach for developing asset management plans, and the role of the asset management system in supporting achievements of the asset management objectives." [9]. The main aim of SAM (Strategic Asset

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Management) services is to enhance strategic risk management and optimize their projects' total portfolio value. More recently, several industry organizations (e.g., Vercity (original HCP Social Infrastructure (UK) Ltd), NHS Property Services Ltd., Faithful + Gould) have started to deliver SAM services to several different types of projects over the O&M phase by establishing their own SAM Units or Departments. In this paper, SAM Units are further specified as the working groups that conduct activities embedded with the organization and stakeholders' long-term vision and value that balance costs, opportunities, and risks of business asset and asset systems. Opposite to the traditional single project-based management routine, the innovative SAM services must be strategically applied throughout all SAM Units' portfolios from different clients. To achieve the aims, SAM professionals need to ensure not only the well-operation of a project through different building maintenance strategies: corrective, preventive, and condition-based [10] but also the optimization of the portfolio value through various means (balancing risk and resources, coordinating decision making about project investments, etc.) [11,12].

To deliver best-in-class asset management services and provide suitable recommendations to determine the strategic level of asset management, SAM professionals need to collect and collate accurate, relevant, and timely data to support the decision-making. Although it becomes a mandate for facilities management teams to provide asset data requirements, there are still many process challenges and inefficiencies faced by the SAM professionals, like the confusion over how to create, exchange, and manage the asset data from construction to O&M phase, without mentioning the data standardization requirements for management at a portfolio level [13,14]. In the operation phase, when the asset data is not accurate or incomplete, a timely recreation process needs to be conducted by the facility manager [14]. For BIM to increase the task efficiency and deliver more 'value' for the building operation, structures and processes need to be re-engineered to accommodate new workflows [15]. The interoperability issue among different BIM tools has also largely limited the achieving BIM 'value' for the whole building lifecycle [16]. Whether COBie's data structure and format could be used for SAM's purpose remains an unexplored area. Various types of information and the relevant data, including the precision and the availability of building assets' physical condition (e.g., damage and degradation), the capital requirement (e.g., the handback condition requirement for PPP projects), and functional requirement (e.g., 24 h operation requirement for data center), will determine the success of SAM.

In order to accelerate SAM Units and fully utilise the information created from the design and construction phases, this research is targeted to address the following research objectives.

1) *Evaluate the SAM services' data quality.*
2) *Analyze and summarize how the BIM handover data can be obtained and managed for the portfolio-based SAM services.*
3) *Explore the way for the SAM Units to reap the strategic benefits of portfolio management fully.*

In order to achieve these three research objectives, this paper attempts to propose a new information flow framework to manage the multi-project environment. A case study is used to evaluate the data quality of a UK-based SAM Unit's portfolio to assess the proposed portfolio-based BIM-integrated information flow framework and renovate the existing SAM data attribute template to a new hierarchical data attribute structure for portfolio-based data management. The case study is conducted by evaluating the SAM Unit's portfolio data quality, identifying the major obstacles for SAM Units' data quality, reviewing the current BIM data handover process, and comparing the data attribute structure with other SAM-related data attribute structures. Then a new hierarchical portfolio-based SAM data structure is proposed to improve the current portfolio-based data management process. In the end, the major benefits for the proposed information flow framework

and data attribute structure and their corresponding contributions are discussed. As a result, the strategic benefits of building portfolio management can be maximized by fully embracing the information created from the design and construction phases.

2. Literature review

2.1. Portfolio management and its common problems in strategic building asset management practices

Portfolio management involves coordinating and controlling multiple projects pursuing the same strategic goals and competing for the same resources. Managers prioritize projects to achieve strategic benefits [17,18]. SAM Units' business goals perfectly align with the fundamental aspect of portfolio theory in the construction that the riskiness inherent in the single project held in a portfolio is usually less than the riskiness of an isolated held project [19,20]. Some researchers have noticed the importance of utilizing portfolio-based strategic management principles in managing the building asset portfolio [21,22]. Although some studies emphasized the strategic approaches' importance in the effective simultaneous management of the portfolio-based built assets, they have not provided the detailed SAM-enabled information management guidance [23–26], not to mention how portfolio-based data management can benefit from a strategic perspective. Although the portfolio management field has developed some global standards and tools [27,28] for practical applications, they are still too general and lack customization for the SAM Units and other FM (facilities management) consultants. Although many portfolio management frameworks and recent research studies have emphasized the dimension of "strategic alignment" in terms of how the projects collectively fulfill the firm strategy and "portfolio balance" among the different types of projects as a reflection of strategic priorities, risk management, and exploitation of synergies [11,29–32], there is a lack of customized portfolio management guidance for SAM professionals, especially over portfolio-based data management.

Deviated from portfolio management's main themes, researchers tried to identify problems and success factors encountered in the portfolio or multi-organizational project management [33,34]. For instance, Elonen and Artto have summarized six problem areas for portfolio management [35], while Ghasemi and colleagues have summarized the portfolio success factors for portfolio management activities [36]. Moreover, many studies have widely recognized information availability as an important factor in portfolio management efficiency [31,32]. In this paper's agenda, Elonen and Artto's six problems (especially the data management) will be used as the major evaluation dimension to assess whether the commonly found portfolio management problems will also be found in the SAM practice.

2.2. Data quality in asset management

Data has been traditionally regarded as the foundation for operational, tactical, and strategic decisions. Without the help of data, managers cannot plan, coordinate and govern the organization's resources to reach for new opportunities, improve the current processes and strike for innovative solutions [37]. "Quality data are data that fit for use by the data consumer" [38], which is the widely accepted definition of data quality. High-quality data that includes internal and external information is crucial for the initial and continuous evaluation of the projects in a portfolio [39]. Without correction, poor quality data often leads to more experience-based judgment than data-driven judgment [40].

Data quality evaluation is challenging because data quality cannot be assessed without context [41]. In asset management, there is very limited research dealing with data quality issues. The Audit Commission has developed a "six-dimension" framework to measure asset management data quality [42]. This framework is designed to assess the public bodies' data quality and help them deal with datasets' hidden

weaknesses. It is suggested that data accuracy, completeness, timeliness and consistency are the most popular data quality dimensions among all kinds of data quality literature from various fields [37–40]. Upon Khan, Uddin and Gupta's 7 V's data quality characteristic model [43], Zhu and Cai [44] have successfully mapped and compiled these characteristics and previously mentioned four popular data quality dimensions together. Their data quality metrics consist of five major dimensions: availability, usability, reliability, relevance, and presentation quality. Zhu and Cai's data quality indicators [44] have been suggested by Heinrich et al. [45] as the needed metrics to evaluate the service application quality. Also, some recent studies evaluate the BIM's information quality for the FM purpose [46]. However, they mainly evaluate the BIM data quality on a few projects, which cannot be directly used for the portfolio-based SAM purpose. Evaluating whether the existing data attributes fit the SAM's purpose is needed to improve the relevance and availability of the existing SAM data quality.

2.3. Frameworks for applying BIM in building asset management

Many scholars and industry professionals have been actively involved in proposing the frameworks that reveal BIM/building data's potential in the asset's whole lifecycle. Some generalized frameworks look at different perspectives of BIM's connection to the built environment from a macro theoretical level [46,47]. For instance, Jung and Joo [47] proposed a BIM framework that lists all the issues related to BIM's practicability for real-world projects. Chen et al. [48] attempted to construct a conceptual framework to bridge BIM and building by summarizing the current BIM-related studies in the built environment. In contrast, Gu and London [49] came up with a collaborative BIM decision framework to better incorporate BIM into their project. Succar [50], instead of looking at connections of BIM to the built environment, set up a new research and delivery framework for organizing the specialized ontology and visual language that was designed specifically to investigate the BIM domain and supply actionable deliverables.

While other scholars have made some progress on frameworks that support the BIM information flow across different project phases, Love et al. [51] pointed out the typical BIM workflow for the asset owner before the "As-Built" Handover Deliverable, except for creating a framework that critically evaluating asset owners' potential benefits. With the advancement of IT and BIM-related information technologies, some researchers have focused on developing a framework for integrating BIM with the Internet of Things (IoT), smart sensors, and web-based systems [51,52].

2.4. Gap of portfolio-based strategic building asset management

With the emergence of needs for portfolio-based strategic building asset management, the industry currently needs a framework to utilize better the information flow provided by different building data collection processes and methodologies (e.g., data from BIM & building asset survey). First, most of the above frameworks are design-based on needs for a single project. In other words, they cannot embrace the building asset portfolio level of intelligence required by many SAM Units. Secondly, the previously mentioned frameworks mainly focus on BIM-integrated day-to-day operation and maintenance delivery. As a result, there is a lack of a strategic "data pool" to store the SAM-related data models and link them with other useful data sources, including asset and defect condition survey spreadsheet, room datasheet, warranty documents from suppliers, internal SAM mandate, and external cost/maintenance guidelines. Therefore, a new framework is needed to identify and store the critical building asset data required for both strategic and operational asset management decisions and make better use of the portfolio-based project data to solve the current "rich" data but "poor" utilization problem.

3. A BIM-integrated portfolio-based SAM information flow framework

To address portfolio-based strategic building asset management issues, we develop a framework to create SAM's utilizable portfolio-based data hub. Creating a SAM data hub to collect, collate, achieve, and store all the project asset data and related documents can strategically manage and benefit data from different projects. In addition, this framework will allow the SAM Units to gain more organizational knowledge to improve SAM core services quality. We try to fill in the blank between the BIM handover and CAFM (computer-assisted facilities management)/CMM (Computerized Maintenance Management) system to enable the real portfolio-based data management for SAM professionals.

To start with, instead of directly linking other non-geometric data from the BIM design model (e.g., Autodesk Revit) to the CAFM system. The data should be firstly cleaned and immigrated into a portfolio-based master data model/database. So, all the imported project data will not continually suffer the data interoperability and standardization issues, and guidance for BIM-integrated portfolio-based SAM information flow can be provided to these projects before the beginning of the real building data handover or transfer.

There are several drivers behind the development of the new BIM-integrated portfolio-based SAM information flow framework. First, it can ensure the update of project data. Specific asset data can be mapped back to the portfolio-based master SAM data model, following the same standardized attribute structure/format. Secondly, it ensures that all SAM Units managed project data uses the same grading and classification systems to analyze the individual project and portfolio in the same language and standard. It would speed up the time-consuming data collection, management, and maintenance processes in the current practice. For instance, if the BIM manager can receive the SAM service required data attribute structure from the client, later in the handover process, a SAM useable data model can be immediately imported into the SAM portfolio-based model/database without requiring the resurvey. In other cases, the standardized building asset condition grading and classification system used across the portfolio allows the portfolio manager to pull out all the required asset data entries from all projects with "a simple click."

The accumulation of handover experience and portfolio-based data migration knowledge is another major design intention for this new information flow framework. This will allow the knowledge and handover data structure learned from the existing SAM projects to be leveraged by the new project's designer or client before the project commission. Designers and contractors can be more aware of the data attribute needed for SAM and other O&M purposes. The missing SAM core data attributes or the time wasted previously in constructing redundant data attributes can be avoided.

Because many SAM services data (e.g., building defect survey report data) and files cannot be stored inside the Master SAM model in the tabular format, there is no portfolio-integrative place for the current BIM handover framework storing the O&M manuals and other project-related information. The new information flow framework (Fig. 1) is designed to include the links (e.g., hyperlinks stored inside the master SAM data model) to these various data sources and recognize their relative importance in the SAM management service processes. This is because facility managers need to spend considerable time searching for the relevant information from the PDF-based mandate or O&M manuals. Whenever new asset documentation needs to be added or replaced (e.g., product warranty information), the corresponding hyperlinks can be easily filtered in the master model and changed.

As a result, both the centralized master SAM database/model and cloud-based project document storage will support SAM Units over core services. After the clients approve these service proposals, the new lifecycle plan or profile will be issued to the day-to-day O&M team and passed to the CAFM system to help schedule more 'intelligent' proactive
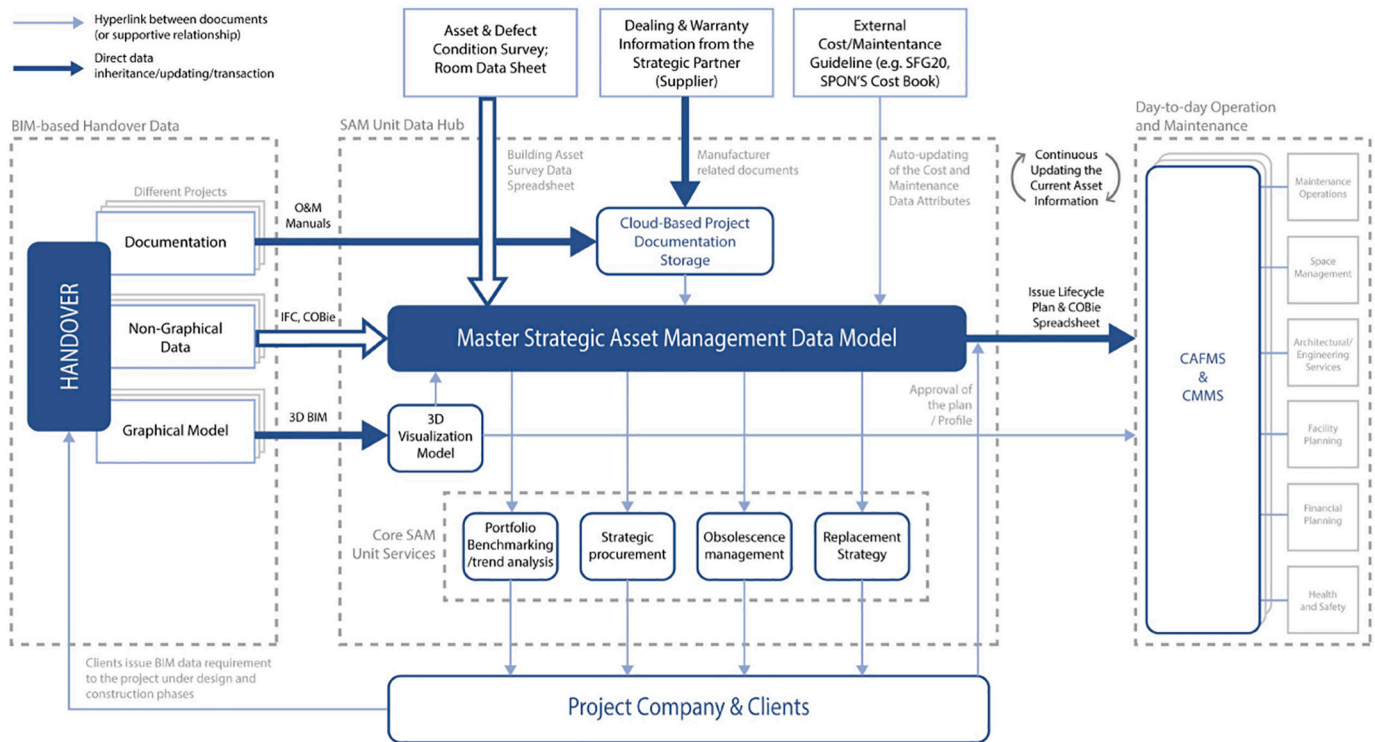
Fig. 1. New BIM-integrated portfolio-based SAM information flow framework.

maintenances. In addition, it is suggested that two important processes highlighted with 'hollow arrow' in Fig. 1 can be further improved and automated with the machine learning based text classification and image classification algorithms. For the data flow from asset and defect condition surveys, the image classification algorithm can help speed up the surveying process by automatically providing asset labels and description suggestions. While for new projects that need to be immigrated into the existing portfolio, the text classification algorithm can automatically assign 'asset type' for standardization.

4. Case study

4.1. A UK based SAM unit

The UK-based SAM Unit was founded in early 2015, inside a UK leading middle-sized SPV (special purpose vehicle) and asset management company – Vercity Ltd. Established in 1997, Vercity provides an all-inclusive suite of general and financial management, company secretarial and technical services over the bid development, construction, and operational phases of the portfolio through intelligent infrastructure and related corporate assets. Currently, there are over 100 projects located across the UK, Europe, and Canada, with asset accommodation excess of 3.5 million m^2, and an aggregate capital value of more than £30 billion.

In this case study, the data model is used to investigate the data quality and its integration with BIM (e.g., COBie spreadsheet template). As part of the UCL and Vercity partnership program, one of the authors directly participated in the case study SAM Unit's day-to-day operation as the data analyst (e.g., being responsible for data cleaning, collecting, and other managing practice, as well as attending the case study SAM Unit's regular or special purpose meetings). This unique position allows authors to get access to the case study SAM Unit's major project documents like SAM project-based data models and monthly meeting records. On-site visits, attending the various SAM Unit meetings and conducting informal interviews with other team members provided the relevant evidence and helped gather the opinions and suggestions about

the current SAM Unit portfolio's data management practice.

The case SAM Unit outlines two major missions: 1) Offering a best-in-class asset management service that provides informed opinions and recommendations to determine strategic, tactical and operational direction; and 2) Collecting, collating and creating accurate, relevant and timely data that allows decision-making, ensures continuity of service delivery safeguards values, and enhances stakeholder objectives. The data model used in this case study includes data concatenated from SAM Unit's eight educational (e.g., primary/secondary schools) and three healthcare projects (e.g., hospitals). Various types of data (e.g., numbers, words, and images) support SAM services collected by SAM professionals. The SAM Unit recently decided to build a centralized building asset lifecycle database to store all the core SAM decision-making data attributes to power the core SAM services. This centralized database is crucial because it provides SAM professionals a platform to analyze, store, manage, and present the SAM knowledge and data. A data quality revision is needed to analyze whether the currently collected building asset lifecycle data's quality can meet the requirements of portfolio-based SAM services.

There are about 170,000 lines of data entries for the whole data model, out of which 130,000 belong to educational projects, and 40,000 come from healthcare projects. The total lifecycle expenditure for all these projects is around £60 million. In the following parts of this section, the data quality of the SAM Unit's lifecycle data model will be critically evaluated.

4.2. SAM attribute list and related data attribute structures

In this case study, to identify the non-geometric data attributes crucial to SAM services and other building operation and maintenance activities, three different non-geometric data attribute structures from both industry and academia were compared and analyzed.

Both the SAM Unit's current model data attribute list (obtained by concatenating all the SAM Unit projects' data attributes) and 2012's COBie data template are used as the major basis for this comparison and analysis exercise. The reason for adopting the current SAM model data

attribute structure is that many data attributes have already proven to be heavily utilized in many of SAM's core activities. Therefore, it can serve as the backbone for developing the new data attribute structure. While for COBie data template 2012, there are three major intentions behind:

1) It is a standard structure that many projects adopt and fit for both operational and strategic levels of building asset management data handover;
2) It will further enable the new SAM non-geometric data to attribute structure to have the ability to immigrate data more easily from the design and construction stages, after identifying the attributes that can be transferred through COBie;
3) It will also help develop the COBie sample template to add more useful SAM and O&M attributes to the future COBie sample template.

Besides these two data attribute structures, this case study also considers the other industry data attribute structures. For instance, Stride Treglown's building object data categorization system [53], which contains the data suggested to be helpful for the O&M practice, has been ranged into four different types (from high to low: Platinum; Gold; Silver; and Bronze) according to their degree of importance [53], as well as, Becerik's data structure of non-geometric data requirement [1] are put into the comparison.

5. Analysis of the case study portfolio's data quality

In this paper, Zhu and Cai's data quality measurement framework [44] is adapted (as the data presentation quality is not directly relevant to the case study) and used to evaluate its quality. Firstly, similar to the proliferation of big data, SAM requires changing the data obtaining manner from single sources to distributed sources (from different projects in the SAM portfolio). Assessing and ensuring the SAM data model's data quality to support decision-making becomes even more important [45]. For instance, data sources' diversity also brings many redundant data types and increases the complexity of the data structure, making data more difficult during the integration. Secondly, compared with the Audit Commission's six-dimension framework [42], Zhu and Cai's data quality metrics [44] are constructed more logically (in two layers), with less definition overlapping with each other.

After reviewing the current SAM Unit's portfolio-based model in the case study, it is not hard to recognize that the current model for SAM has not scored well in all six second-order dimensions for the data quality. The results of data quality evaluation are summarized in Table 1.

5.1. Reasons for the poor quality of SAM Unit's portfolio-based model

Through the case study analysis, it is suggested that several major reasons are responsible for the poor quality of SAM Unit's portfolio-based model in the case study:

A. The lack of critical data attributes, as well as the existence of redundant data attributes

Professionals in the case study commonly lack clear guidance over the types of data attributes put into BIM or other forms of project handover documents. This phenomenon stops the FM and SAM from fully functioning. As a result, FM and SAM professionals suffer from both the lack of important data attributes and the overcrowded redundant attribute list.

B. The lack of guidance for SAM specific data attribute structure

Although maximizing portfolio-based building asset management's strategic benefits, keeping all the useful data attributes is encouraged. Given the limited time and budget for SAM database construction, SAM professionals and FM managers need more guidance to decide different

Table 1

Summary of case study's data quality requirements against reality.

First Order of Data Quality Dimensions	Second-Order of Data Quality Dimensions	Data Quality Requirements / Reality	Summaries of The Data Quality Requirements / Reality
Availability	Timeliness	Requirement	Capturing data and making it available for use within a reasonable period [42].
		Reality	An average four-month time span from data collection till the final reprofile report approval is expected.
Usability	Credibility (Validity)	Requirement	Recording the data in compliance with relevant requirements (e.g., rules set by professional body and specifications stated in SAM service contract) [42].
		Reality	There is currently no customized guideline that the SAM Unit can follow to extract various data from building asset survey and CAFM/CMMS or COBie Spreadsheet export from BIM to build the portfolio-based asset lifecycle data model. Different projects use different naming systems or attribute specifications. New asset categories from the new project increase the difficulty of requirement compliance at the portfolio level.
Reliability	Accuracy	Requirement	Data can be defined as accurate if it fits its intended purpose, with a clear and detailed representation to support the target activity [42].
		Reality	In many cases, the existing data from the project site, project general manager, and client has been outdated and lacks the required detailed information for SAM services. An annual or more frequent periodic-based asset information updating is required to monitor building assets continuously.
	Consistency	Requirement	Data consistency is ensured by a stable and consistent data collection procedure across the collection processes over time [42].
		Reality	Surveyors found it challenging to find specific or rigid guidelines for assessing a particular building element. Surveyors are

(continued on next page)

Table 1 (*continued*)

First Order of Data Quality Dimensions	Second-Order of Data Quality Dimensions	Data Quality Requirements / Reality	Summaries of The Data Quality Requirements / Reality
			likely to fluctuate in their surveying performance in their surveying exercise (e.g., using different asset naming, category, and description for the same asset).
	Completeness	Requirement	The completeness of data is ensured when the deficiency of a component will not impact the accuracy and integrity of multi-component data [44].
		Reality	The current absence of 'year installed' & 'manufacturer' information in SAM's model data hindered the SAM unit's 'Portfolio Benchmarking' & 'Strategic procurement' exercises.
		Requirement	Data relevance is about capturing the data that fit for data collection purpose [44].
Relevance	Fitness	Reality	In many cases, not all useful information is provided, and not all the available information is useful. In other projects, some of the information attributes are considered to be redundant

data attribute groups' priorities. So, the attributes groups with higher priority will be concatenated into the final database firstly.

C. The lack of guidance for a BIM-integrated portfolio-based SAM information flow framework

It is recognized in the case study SAM Unit, building O&M professionals have not realized and explored the possible way to import SAM-related data from design and construction phases through BIM, especially for those non-geometric data. Unfortunately, it is still not feasible to regularly update the 3D BIM model on the original BIM design software applications (e.g., Autodesk Revit). As a result, the data inherited from the BIM handover process must be either maintained in the CAFM/CMM system or the Excel documents built by the SAM Unit. While for CAFM/CMM system data, even though much data from these systems is task-based rather than asset-based, its portfolio-wide differences (e.g., different projects use different CAFM systems) have stopped it from fully gaining portfolio-based SAM services benefits (e.g., strategic procurement, asset maintenance benchmarking) that could be enjoyed by managing data in a portfolio based centralized model.

D. Current project data and SAM models have not been maintained and standardized promptly.

There is no sufficient financial budget for projects in the case study to maintain the data quality given the fixed-rate payment for many current SAM projects. Data maintenance is positioned behind many core SAM services. In other words, if there are no other strategic benefits (e.g., the opportunities for strategic (bulk) procurement/obsolescence

replacement that could bring new sources of income) or a more cost-effective way of maintaining the current portfolio's model, SAM Units are less likely to spend a considerable amount management resources on maintaining the project data in good condition.

E. More automated and cost-effective means are needed to speed up the data collection, management, and maintenance processes.

The current data collection, management, and maintenance processes (including data recategorizing, data cleaning, and data querying) still largely rely on timely and error-prone manual efforts, which has constrained the time that SAM professionals could have been spent on other more value-creating and strategic activities.

5.2. Current BIM data handover framework

According to British Standards Institution (BSI), the Asset Information Model (AIM) that was handed over to the building O&M phase includes three different types of information: the Documentation, Non-Graphical Data, and Graphical Model [54]. For instance, non-geometric (non-graphical) data (e.g., IFC and COBie files) is handed one-off to CAFM/CMMS. Other information like O&M manuals and 3D graphical models supported by BIM is used majorly as supportive information. However, there are some problems with the current BIM-based data handover process.

First and foremost, the current one-off direct data handover process is fairly limited to its project-oriented nature. It does not allow a SAM utilizable portfolio-based data hub to be created to store and share the data about different projects. In other words, data from different projects cannot be strategically managed and benefit each other. For instance, if a cheaper and more durable floor manufacturer is found, SAM professionals cannot extract data easily from different projects to develop a floor budget profile as a proposal for this new strategic procurement opportunity. As there is no SAM data hub to collect, collate, achieve, and store all the project asset data and related documents, the SAM Unit's opportunity to gain more organizational knowledge to continuously enhance their productivity is lost.

Secondly, the current framework lacks the capability to provide the current building maintenance and operation data to the other relevant projects inside the SAM Unit's portfolio. For instance, if the original radiator heating is replaced with radiator heating produced by other manufacturers, in practice, none of the data will be effortlessly shared with other projects.

5.3. Evaluation of data attribute structure

Unfortunately, there is no widely accepted portfolio-based SAM data attributes structure. Therefore, it is worth comparing the current temporary SAM Data Model template with the COBie example template, Becerik Gerber's data structure [1], and Stride Treglown's required data attribute list for the University of the West of England (UWE) project [53]. In this section, the SAM Unit model attribute structure was analyzed following three steps: 1) By reviewing the percentage of the data entries for each SAM attribute (showed in Fig. 2), attributes with less than 70% of data entries were filtered and colored with grey color; 2) All the existing data attributes inside the SAM Unit's model template were reviewed, and only the cells (inside Fig. 2) of suggested useful attributes were filled with different colors. In other words, some of the redundant, formula-based, or secondary attributes were excluded from discussion in this case; 3) all the attributes inside the current SAM model were matched against the corresponding attribute from the other three different attribute structures (Appendix A).

For project data attributes, none of the COBie sample spreadsheets, UWE data entries, or Becerik's data structure contains the project type data. It is suggested that, for the better integration and identification of the COBie data or other types of data sources from new projects and the
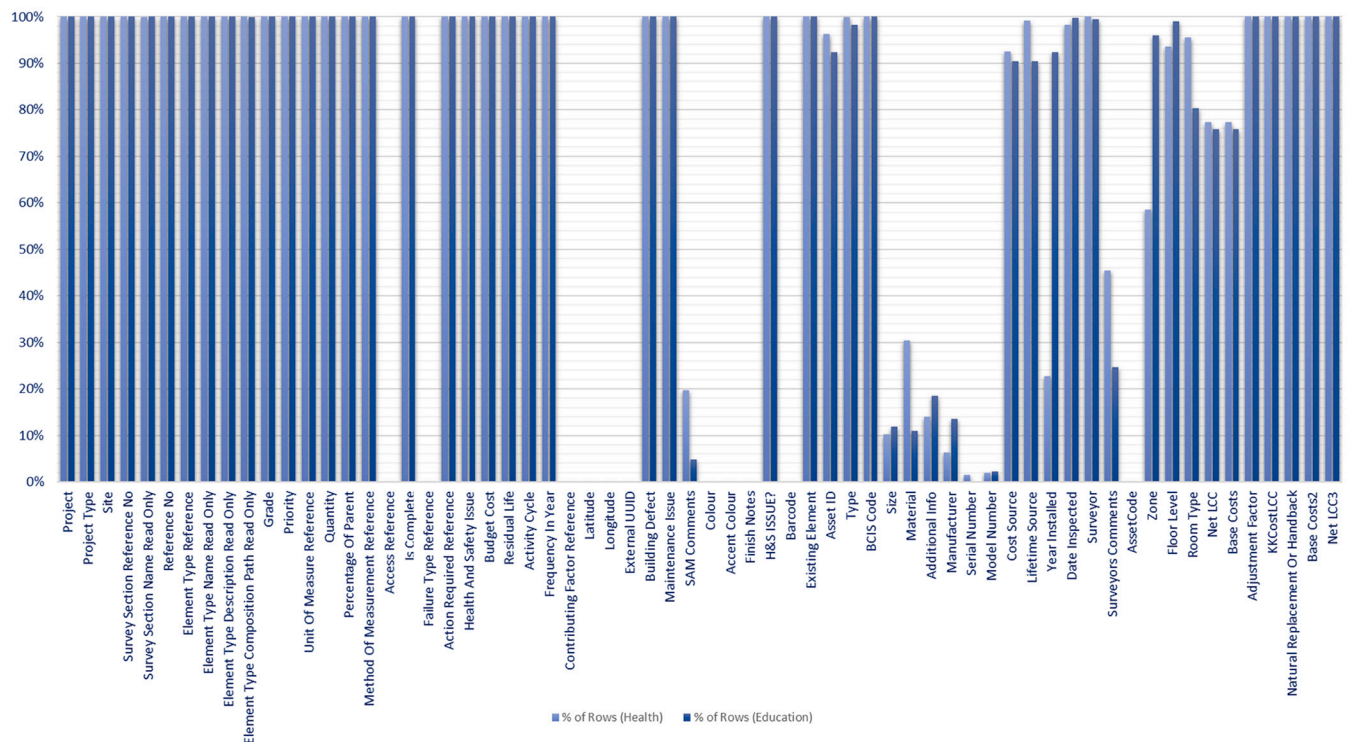
Fig. 2. Percentage breakdown data attribute healthcare against education.

existing SAM portfolio-based model, it is necessary to contain the project data attributes inside the COBie sample spreadsheet and SAM centralized database.

For building component's geographic attributes, the COBie sample spreadsheet is shown to provide all the SAM model required attributes. According to Fig. 2, the percentage of data entries for "Latitude" and "Longitude" less than 70% is worth recognizing. More explicitly, the data completeness of these attributes (named 'CoordinateXAxis' & 'CoordinateYAxis') has the potential to be improved by using data imported from the COBie spreadsheet. By doing that, the causal relationship of many damaged components can be easily linked and calculated through the calculation of Euclidean distance of the damaged building components or show their positions in the floor plan or 3D geometric model inside the BIM so that the SAM professionals can perform analysis and estimate the potential risk level of project's hazard remotely. It is also suggested that both 'Latitude' and 'Longitude' information is not required in either UWE's attribute list or Becerik's data structure. SAM Units core information-related data attributes are a group of attributes suggested providing SAM services' data foundation. It is not hard to realize from SAM Unit's existing core data attributes (Fig. 2) that a very important attribute is "Manufacturer," which lacks sufficient data. This attribute is crucial for strategic procurement purposes. For instance, if SAM professionals want to estimate the potential financial saving of strategic procurements over the next five years for replacing a specific group of similar building components with a strategic partnership supplier's product (e.g., air-conditioning equipment produced by Daikin), one of the easiest ways is to find out all the target building entries by filtering all the competitive brands' names (e.g., Mitsubishi Electric; Panasonic; Haier; etc. for the case of Daikin). As all three different data structures are required to import this data, it is fair to suggest that if the SAM Units data model can import these data attributes from the COBie spreadsheet, there will be a significant improvement in the portfolio-based strategic procurement exercise.

Unfortunately, many key attributes are still missing in all the current COBie templates, Becerik's data structure, and UWE's attribute list. It is important to recognize that missing these attributes could substantially

hinder many SAM Units' core services. For instance, attributes like "Quantity," "Residual Life," "Activity cycle" are the main attributes used to make strategic building assets' lifecycle planning. If these attributes are missing or not provided from the design and construction phases, enormous time and effort would be spent recollecting them from the project.

For non-core SAM data attributes, although the lack of these attributes will not directly affect the SAM Unit's core services like lifecycle planning, strategic procurement, etc. They are still useful in the detailed analysis of the SAM Unit's core services and play an important role in helping many non-core SAM Unit exercises (e.g., assessing the non-monetary aspects of the projects). Unfortunately, unlike SAM's core data attributes, less than 60% of the attributes (see Fig. 2) in these topics have more than 70% of the data entries. Fortunately, five of these seven incomplete data attributes exist in the COBie sample attribute list. Therefore, many data attributes can be potentially provided through the COBie spreadsheet. Unfortunately, there is only one attribute for Stride Treglown's list of categories: "Barcode Ref," which could match the existing SAM Unit attributes. The attribute coverage for Becerik's data structure is even worse.

Surprisingly, after cross-checking the data attributes of SAM Units and Stride Treglown, it is suggested that there are many useful Stride Treglown attributes: "SFG20 planned maintenance Scheduling"; "Service Contract duration"; "Warranty Start Date"; "Warranty Duration"; "O&M information"; "Test/Commissioning Sheet"; "Test Certificate"; "Manufacturer's Instructions"; "Fire Rating" that can be further integrated into the existing SAM Unit attribute list or be externally linked. In the case study SAM Unit, some of this data is kept previously in PDF-based O&M manuals.

6. A new portfolio-based SAM data attribute structure

After a rigorous comparison process, a new hierarchical portfolio-based SAM data attribute structure (Fig. 3) is proposed to provide all SAM professionals and building asset owners with better guidance over the most suitable data attributes they can rely on when building their
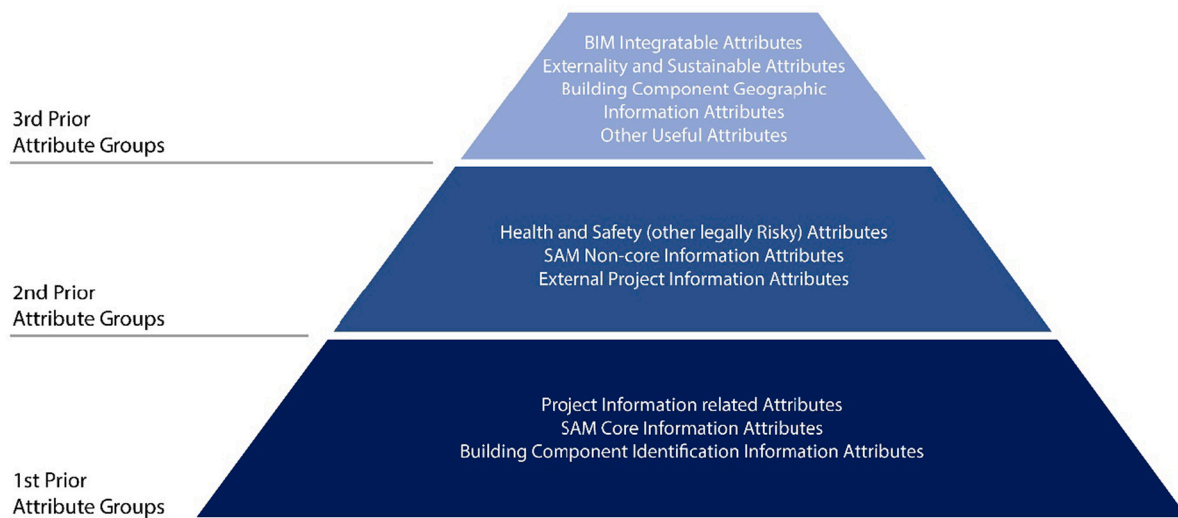
Fig. 3. A hierarchical portfolio-based BIM-integrated SAM data attribute structure.

own portfolio-based SAM data models. This will also help SAM professionals issue and finalize BIM data requirements in the design and construction phases. Many attributes that originally did not exist inside the case study's SAM Unit data attributes structure are considered in this new data attribute structure. In addition, some useful attributes are integrated into the current temperately concatenated SAM Unit data attribute list to deliver a more stratified data structure.

First, all attributes suggested useful for the SAM purpose are divided into ten groups (see Appendix C). According to their relative importance for portfolio-based SAM services, these groups are further ranked into three hierarchical levels. For instance, the three attribute groups in the first (bottom) priority level contain the most crucial SAM data attributes for proceeding with all the portfolio- and project-based SAM core services (e.g., strategic procurement, portfolio benchmark, etc.).

To further improve the robustness of the asset lifecycle planning, taking other non-monetary factors (e.g., safety factors) into consideration, more data attributes are required to be considered, including risk considerations (e.g. 'risk' attribute), health and safety impact (e.g. 'Type (Issue)'), asset downtime (e.g. 'LeadIn Time' & 'LeadOut Time'), and the links to other operation and maintenance documents (e.g. 'File (e.g., the hyperlink of the filename)'). These data attribute groups stay at the second level of this data attribute structure.

While at the top-level, if a more in-depth analysis is needed to figure out the more detailed damage impact of some hazards (e.g., water leakage), building component geographic data attributes (e.g., 'CoordinateX,' 'CoordinateY,' and 'CoordinateZ') can be used to find out all the potential affected nearby components.

It is worth noticing that although this data structure has attempted to provide a universal SAM data attribute importance ranking when selecting an organization's own portfolio data attribute list from this new data attribute structure, the characteristics of portfolios should not be ignored. For example, suppose FM-enable BIM data is well prepared for most projects inside the service portfolio. In that case, there is no doubt that the 'BIM integratable attribute' data group should be included.

Given this new data structure, SAM professionals and the client can now prioritize different data attribute groups during the data collection, handover (e.g., from BIM), and validation processes regarding their own budget and timeframe.

7. Discussion

7.1. Benefits of new information flow framework in managing the multi-project environment

The benefits for a new information flow framework are illustrated regarding Elonen and Artto's six problems in managing a multi-project environment [35] (the detailed information is included in Table 2):

1) Project level activities: The developed information flow framework benefits the project level activities by enabling the transfer of the SAM and building O&M phase BIM data requirements to the pre-O&M phase and lowering the manual cost of asset status checking and monitoring. Thereby the frequent portfolio-based project progress monitoring can be achieved cost-effectively.

2) Portfolio level activities: The developed framework guides for promoting portfolio level activities with fewer tasks overlapping and redundant project-based works, as all the project related data is stored and managed in a centralized and standardized manner, as well as letting feedback circulate unimpededly between projects given a much lower communication cost.

3) Management of project-oriented business: The developed framework clearly defines the portfolio's management role for SAM professionals (representing the clients' best interest). SAM professionals take more ownership of the data and risk management of their client's portfolios.

4) Data management: The developed information flow framework enables more portfolio-based SAM data for individual projects and allows this data to flow effortlessly between the different project leaders. This is allowed by building a centralized SAM data model, where all the SAM project leaders can easily query the required project and portfolio data. The new framework defines the different BIM data handover information flow to SAM data hub and the information flow from SAM Unit Data Hub to the rest of the data sources and benefits O&M phase stakeholders.

5) Commitment, roles, and responsibilities: The developed framework provides a new perspective on the decision-making process of the projects and portfolios. Upon implementing the portfolio-based information flow framework, the project company and clients will receive the portfolio-based suggestions and lifecycle plan, providing strategic alignment for the project work.

6) Resources, competencies, and methods: The structure of the newly developed information flow framework can be used as the backbone for further integrating other SAM and FM-related guidelines, methods, and technologies.

Table 2

Summary of proposed improvements of new information flow structure to the multi-project management environment.

Elonen and Artto's Six Problems		How Can New Information Flow Structure improve these Problems?
Major Areas	Sub Areas	
Project level activities	Improper implementation of the pre-project phase	The primary benefit that the new information flow framework can bring to the pre-project phase's implementation is that it enables transferring the portfolio-based SAM and building operation and maintenance phase's BIM information requirement to the pre-operation phase of the building project.
	Project progress monitoring is infrequent	Since all of the building asset-based entries need to be recategorized according to the new SAM database's category structure, the same asset group (even from different organization's projects) will be able to be easily screened out and filtered, which will lower the manual-cost of asset status checking and monitoring.
	Overlapping and redundant tasks within one project and among the portfolio	Because not all the project-related data is stored centralized in the underdeveloped SAM database, the new information flow framework is required to streamline many of the previous overlapping activities and tasks that have previously been conducted isolatedly and repetitively.
Portfolio level activities		Similarly, with the help of a new information flow framework, many project-level data analysis tasks can be condensed to a portfolio-level task that is done all at once in a cost-effective manner. So that both the project and portfolio-level feedback can be given to every specific project.
	No feedback is given at the project level	
Management of project-oriented business	No defined owner, business, or personnel strategy for portfolio	It was also suggested by this new information flow model that the SAM Unit should take ownership of the information and risk management of its client's portfolios.
Information management	Lack of information on projects. Inadequate flow of information across the organization	Like other general multi-project management scenarios, this case study's portfolio management also suffered a severe information shortage and inadequate information flow across different bodies. The primary cause of this situation is never the quantity of the project information is shorted, but the shortage of FM and SAM useable data attributes (e.g., manufacturer, product activity cycle, installed data information, etc.) and the

Table 2 (*continued*)

Elonen and Artto's Six Problems		How Can New Information Flow Structure improve these Problems?
Major Areas	Sub Areas	
		portfolio perspective data attributes (e.g., building element replacement cost benchmark information, project performance evaluating criteria, etc.). Combined with the new data attribute structure developed in this research, the prioritization can be clearly set between the SAM/FM core data attributes and the rest of the none-essential data attributes.
	Information flow from projects to the other parts of the organization, and vice versa, is not defined	This new information flow framework will help the stakeholders of the building project to embrace a new form of the information transaction process and understand how the project information can be more intelligently managed and benefited back to the day-to-day building operation and maintenance, as well as the clients by aggregating and linking all the SAM required information to the master strategic asset management database.
	No common database of projects	The other major benefit of embracing this new information flow framework is building a portfolio-based centralized database for all projects within a defined model responsible unit - the SAM Unit.
Commitment, roles, and responsibilities	Unclear roles and responsibilities between portfolio decision-makers and the other parts of the organization & Nonclear roles and responsibilities at the project level	Although the new information flow framework has not clearly defined detailed roles and responsibilities between the SAM professionals and other parts of the organization (i. e., project general manager), the new information flow framework provides a new perspective of thinking about the projects and portfolio decision-making process. Because, instead of making project-level decisions based solely on the project's data, both the portfolio and project-level information can now be fueled into the decision-making process.
	Management does not seem to support project work	Upon implementing the new information flow framework, the project company and clients will receive the portfolio-based suggestion and lifecycle plan, providing strategic alignment for the project work.
Resources, competencies and methods	Methods and guidelines for portfolio evaluation and project planning and management are inadequate	Although the detailed and specific methods and guidelines for portfolio evaluation and project planning and management will not be covered in this research, the structure of this

Table 2 (*continued*)

Elonen and Artto's Six Problems		How Can New Information Flow Structure improve these Problems?
Major Areas	Sub Areas	
		new information flow framework can be used as the backbone for the further integration of more detailed SAM and FM-related guidelines, methods, and technologies.

Furthermore, compared with Munir and his colleagues' BIM-based asset management integration framework [55], which more focus on identifying the importance of 'discovery phase' as the key process in capturing asset information towards BIM-based integration and the business value of BIM-based integration, the proposed new information flow structure is designed to compromising the needs of asset information integration for a portfolio rather than a single project-based BIM and asset management systems integration. Different from some of the latest BIM-based frameworks like Santos's BIM-life cycle assessment (LCA)/life cycle costing (LCC) framework [56], whose concentration over the environmental and economic analysis, the proposed BIM-integrated portfolio-based SAM information flow framework is more focused on the client-oriented strategic level portfolio-based asset management. It is important to recognize that the proposed framework has pointed out a portfolio-based data handover framework that is different from the traditional COBie (or Computer-Aided Design (CAD)) files to the CAFM handover process [51].

7.2. Benefits of SAM-enabled data attribute structure

Until recently, professionals in the case study SAM Units still have not reached the final agreement over SAM services' exact data attributes. The temporary SAM Unit's portfolio data attribute list is obtained by concatenating the different projects' data attributes. In other words, the SAM data attribute template shown in Appendix A is not yet a matured data attribute structure that has the proper selecting and grouping of all relevant and necessary attribute groups. Through the case study, it is identified that there are three major benefits for the construction and further improvement of the existing temporary SAM model data attribute structure.

Firstly, the new structure provides the necessary attributes that empower the core SAM services. This means that several compulsory attributes need to be contained in the new data attribute structure. For instance, 'quantity,' 'base costs,' 'activity cycle' (or 'lifetime'), and 'residual life' can be regarded as the essential attributes needed to support the core activity of the SAM Unit. This is because they can provide information for planning and mitigating the risk of the asset lifecycle activities across the project concession period.

Secondly, the new model data structure can now compromise the needs of different projects. The attributes in the template should be carefully selected to contain as many useful and necessary attributes as possible. In many projects, useful data attributes like 'manufacturer' and 'materials' currently lack sufficient data entries (Appendix A). It is suggested that they are worth keeping and need to be integrated into the centralized database. Different from some of the existing BIM frameworks that actively integrate BIM with the Internet of Things (IoT), smart sensors, and web-based systems [51,52], the proposed portfolio data attribute structure is more concentrated on the asset data that is more crucial for the asset replacement planning and strategic procurement.

Finally, this new data attribute structure must guide the priority against different data attribute groups and clearly distinguish the difference between different attribute groups. This will allow SAM and other FM professionals to customize their own portfolio- or project-

based data attribute structures to suit their own needs and budget. This means, compared with Alnaggar and Pitt's conceptual framework of managing BIM/COBie asset data [14], the raised new data attribute structure has considered not only the existing COBie data attribute structure but also the data attributes that meet the requirement of the portfolio based strategic asset management.

7.3. Contribution of the portfolio-based information flow framework

The new information flow framework is designed to enlighten SAM professionals to include all potential ways of obtaining project data, potentially shortening the time length of the data collection process by selecting the most appropriate data collection methods. For example, suppose the SAM and FM data is well-prepared inside a newly handed over project's BIM documents instead of resurveying all the building assets again to recollect the data needed for producing the SAM lifecycle report. In that case, the project's COBie data combined with the random sample survey can be used instead.

Secondly, the new information flow framework provides guidance and a mind map for SAM professionals to follow during the data management and handover processes. As a result, the data validity can be further enhanced.

Thirdly, the new centralized portfolio model/database will enable more accurate data querying and bulk updating. It is stored centrally and kept in the same standardized format (e.g., using the same building element category structure).

Fourthly, rather than developing specifications or rules rigidly for building asset defect survey and condition assessment, the new information flow structure gives new ways of gaining collective asset knowledge to improve the data consistency. For instance, when more and more data conditions, variables, and comments are collected regarding a particular type of building element in a centralized database, SAM professionals and surveyors can improve their survey consistency for many building elements, based on the previous successful examples from the whole portfolio.

Lastly, the new information flow framework for SAM will enable the asset data like 'year installed' and 'manufacturer' to be further passed and maintained in the building O&M phase (details summarized in Table 3).

7.4. Contribution of new data attribute structure

SAM professionals can self-check to find out which particular groups of data attribute categories in the new data attribute structure need to be surveyed or collected further with the help of the developed data attribute structure. SAM professionals can properly prioritize their data attribute collection using the hierarchical BIM-integrated portfolio-based SAM data attribute structure. Therefore, the time length of data collection can be shorted by excluding the collection of unnecessary data.

Secondly, although the new data attribute structure in this paper is not intended to provide the detailed data attribute specification for surveying each building element, other SAM professionals or facilities managers can still use this new data attribute structure as the basis to build their own portfolio-based attribute specifications.

Thirdly, the new data attribute structure for SAM enables the client to provide portfolio-oriented attribute requirements for the BIM data producer in the design and construction phases. If all these required attributes can be provided in the COBie format, they can be used as the initial benchmark data for future comparison. In the meantime, the new data attribute structure ranks and separates different SAM data attribute groups with their priority hierarchy positions and function types.

Fourthly, the new data attribute structure will enable clients and SAM professionals to give more specific BIM handover requirements (e. g., compulsively include manufacture and date of installed data attribute) that further enable the BIM's utilization in SAM's other building

Table 3
Summary of data quality improvements given by new information flow structure and new data attribute structure.

First Order of Data Quality Dimensions	Second-Order of Data Quality Dimensions	Data Quality Reality	How Can New Data Attribute Structure improve these Phenomenons?	How Can New Asset Information Flow Structure improve these Phenomenons?
Availability	Timeliness	An average four-month time span from data collection till the final reprofile report approval is expected.	SAM professionals can now easily self-check which particular groups of data attribute categories in the new data attribute structure that are needed to be surveyed or collected, as SAM professional can properly prioritize their data attribute collection with hierarchical BIM-integrated portfolio-based SAM data attribute structure.	The new information flow framework will enlighten SAM professionals to include all potential ways of obtaining project data, which can potentially shorten the time length of the data collection process by selecting the most appropriate data collection methods.
Usability	Credibility (Validity)	Although SAM Unit professionals and out-sourced surveyors do comply with the project-based requirements in their data collection, there is currently no customized guideline that the SAM Unit can follow to extract various data from building asset survey and CAFM/CMMS or COBie Spreadsheet export from BIM to build the portfolio-based asset lifecycle data model. Different projects use different naming systems or attribute specifications. New asset categories from the new project increase the update frequency of the model asset category list, which increases the difficulty of requirement compliance at the portfolio level.	Other SAM professionals or facility managers can still use this new data attribute structure as the basis to build their own portfolio-based attribute specifications.	The new information flow framework will provide guidance and a mind map for SAM professionals to follow during the data management and handover process to enhance data validity.
Reliability	Accuracy	In many cases, the existing data from the project site, project general manager, and client is outdated and lacks enough detailed information for SAM services. A significant amount of budget needs to be spent to update the building asset information and recollect missing data in many projects. An annual or more frequent periodic-based asset information updating is required to continuously monitor the condition of building assets. The asset category classification process is still done manually, which is very time-consuming and error-prone. More evidence is needed to ensure the reliability of the survey data collection.	The new data attribute structure for SAM will enable the client to provide an attribute required for the design and construction phases BIM information producer. Similarly, the new data attribute structure can help label all SAM data attribute types with their priority hierarchy positions and function types.	The new centralized based portfolio database will enable more accurate data querying and bulk updating, as it is stored centrally and kept in the same standardized format (e.g., using the same building element category structure), as well as provides the guidance to link the materials to the centralized building data model pool, which will enable the providing of more evidence to the specific building element.
Reliability	Consistency	Surveyors found difficulties finding specific or rigid guidelines for assessing a particular building element (e.g., assessing the vinyl flooring condition). Surveyors are likely to fluctuate in their surveying performance in their surveying exercise (e.g., using different asset naming, category, and description for the same asset).		Rather than develop specifications or rules rigidly for building asset defect survey and condition assessment, the new information flow structure will enlighten new ways of gaining collective asset knowledge to improve data consistency. For instance, when more and more data conditions, variables, and comments can be collected regarding a particular type of building element, SAM Unit professionals and surveyors can improve their survey consistency for this building element based on the previous successful examples heuristically.
Reliability	Completeness	The current absence of 'year installed' and 'manufacturer' information in SAM's model data hinders the SAM unit's 'Portfolio Benchmarking' & 'Strategic procurement' exercise. The lack of 'manufacturer' data attribute also damages the completeness of the data by decreasing the falsifiability of the asset classification and querying.	The new data attribute structure will enable clients and SAM unit professionals to give more specific BIM handover requirements (e.g., compulsively including manufacture and date of installed data attribute) that further enable BIM's utilization in SAM and other building facility management services.	The new information flow framework for SAM will enable asset information like 'year installed' and 'manufacturer' to be further passed and maintained in the building operation phase.
Relevance	Fitness	In many cases, not all useful information is provided, and not all the available information is useful. Some information attributes are considered to be redundant in many projects.	The suggestions have been given for providing what useful information should be collected and given for BIM-enabled SAM and facility management application. Many of the redundant data attributes have been removed from the original SAM data attribute structure.	

FM services.

Finally, the guidance has been given to provide what useful data should be collected and provided for BIM-integrated SAM and FM application. Many redundant data attributes have been removed from the original SAM data attribute structure (details summarized in Table 3).

Given the new BIM-integrated portfolio-based SAM information flow structure and the new SAM data attribute structure, this research enables the master SAM database to connect to various data sources to support the real portfolio-based SAM services for the clients and other project stakeholders. The problems and solutions identified in this research paper open another window to BIM-integrated portfolio-based data management.

This research made a unique contribution to providing a new SAM customized data attribute structure to help SAM professionals and other building stakeholders build their own customized data attribute structure for their portfolios. The proposed information flow framework and data attribute structure provide solutions for the lack of information requirement problem of portfolio-based BIM implementation in the O&M phase raised by many researchers [1,2,57]. This study also provides the guidelines over the necessary information content and format needed for the BIM's O&M phase applications [1,58]. The proposed portfolio-based information flow and data attribute structure also meet the literature gap of portfolio management and data quality management in the O&M phase [30,40].

7.5. Towards portfolio innovation for traditional building project management

In this section, the innovations made by this study are summarized as follows:

1) Innovations towards evaluating the portfolio-based building management's data quality: This study has recognized the knowledge gap of lacking data evaluation methods and research for the O&M phase data. By evaluating the data quality of the case portfolio, this study explores the applicability of applying a non-native construction-specific data quality metric in evaluating the data quality of the portfolio-based SAM data quality model.

2) Innovations brought by portfolio-based information flow framework: Firstly, this study has inventively pointed out the fact that there is a portfolio data handover gap between the traditional BIM-based data handover from design and construction phases (e.g., in COBie spreadsheet format) to the O&M phase (e.g., stored and managed in CAFM and CMMS) [1,5,7,58]. To close this data handover gap, this study has introduced the master strategic asset management data model and outlined some of the core SAM services to support the necessity and applicability of portfolio-based data management theoretically. Secondly, the raised information flow framework supplements several important data sources (e.g., asset & defect condition survey; supplier warranty information; external cost/maintenance guideline) that were originally missing from the traditional BIM data handover process for the O&M phase building asset data management [1,57]. Identifying these sources is important as they are also required to support portfolio-based core and non-core SAM services. Thirdly, the study also suggests that there are two specific data flow processes (the handover and migration process of the new project to the master SAM data model and the data collection process of the defect and condition survey) that can be further improved and automated through the machine learning based algorithms. This allows the framework to be integrated with machine learning algorithms.

3) Innovations brought by portfolio-based SAM data attribute structure: Firstly, this study has also innovatively pointed out and filled the knowledge gap of data attribute management structure guidance needed for managing a portfolio [1], which is often ignored under a single project-based management mindset. Secondly, by innovatively comparing both the existing data attribute list from the academy [1] and

industry [53], this study closes the knowledge gap by highlighting the characteristics, enabled asset management activities, and the importance of prioritizing different data attribute groups. Providing this new portfolio-oriented data attribute ranking method is important. It guides the researchers, portfolio data analysts, general project managers, and surveyors on customizing their data collection or management template across the portfolio to enable different levels of SAM services. Thirdly, this study has also provided new theoretical guidance over evaluating existing data attributes in the sample COBie data template. This helps evaluate the usefulness of existing data attributes provided by BIM from the design and construction phases and find out the missing data attributes needed for portfolio-based data management. This bridges the knowledge gap of BIM information for portfolio-based data management.

8. Conclusion

This research used a case study to examine the SAM Unit's portfolio data and reveal the current data quality for portfolio-based data management and the differences between various existing data attribute structures. The problems that limited the SAM data model quality and obstacles that hindered achieving BIM-integrated portfolio-based SAM data handover and management processes are identified and addressed.

There are several findings from this case study SAM Unit, addressing the unsatisfied data quality of the SAM's existing project-based data model: 1) the missing of critical data attributes as well as the existence of redundant data attributes; 2) the lack of guidance for SAM specific data attribute structure; 3) the lack of guidance for a BIM-integrated portfolio-based SAM information flow framework; 4) the lack of maintenance and standardization for current project data and SAM model; and 5) the lack of more automated and cost-effective means to speed up the data collection, management, and maintenance processes. The lack of guidance for a BIM-integrated portfolio-based SAM information flow framework has double confirmed the research gap of lacking a framework to store the building data required for portfolio-based strategic and operational asset management decision-making. In the light of literature review and a case study, a new BIM-integrated portfolio-based SAM framework and a BIM-Integrated portfolio-based SAM data attribute structure are proposed to improve the data quality of the current SAM Unit's data models and prioritize different data attribute groups in the multi-project environment.

From this case study, it is recognized that although the SAM Unit has conducted a quality assurance process to improve existing SAM project data quality, there are still many problems and limitations that can be found when evaluating the current SAM Unit data with different data quality dimensions. The current project-based O&M phase data management nature is the major reason limiting the SAM Unit data quality for portfolio-based SAM applications. Secondly, this paper summarizes the different non-geometric SAM-related O&M phase data requirements and their relative priorities for SAM service applications. Despite the traditional way of obtaining SAM lifecycle modeling data from building condition and defect survey, this paper has also evaluated the possibility of getting more completed portfolio-based SAM data or survey missed data like 'Manufacturer' from the building design and construction phases through BIM. Overall, the information flow framework and data attribute structure developed in this paper have provided specific guidance over how the SAM Units and the client can embrace portfolio-based strategic benefits.

Despite the benefits of raised information flow framework and data attribute structure, this research has some limitations. Firstly, although the case SAM Unit covers both the educational and the healthcare project, the detailed data attribute structure might need to be further amended slightly for encountering the need of some special project types (i.e., data center). Secondly, as all the project data collected in this research's case study came from UK-based projects, the result of data attribute quality analysis might not be equally applied for building

projects outside the UK.

It is suggested that further research could be carried out in the following areas. First, although this research has proposed the new information flow framework and data attribute structure, it does not cover the discussion over the legal obligation and the roles of different parties under this new BIM-integrated portfolio-based SAM information handover and management scenario. More studies are needed to evaluate the potential legal obstacles and risks that could potentially occur during this portfolio-based data management practice. Secondly, although section 3 highlights the potential processes that can be automated (e.g., Image Classification) in the raised new BIM-integrated portfolio-based SAM information flow framework, further research needs to be conducted to evaluate the applicability of these automation techniques and whether building asset data quality can benefit from the machine learning-based automation techniques. Thirdly, although this research

has raised and realized the new frameworks and methods for BIM-integrated portfolio-based building data handover and management, it does not cover much about the portfolio-based building data management theory. Therefore, further research can look at how management theory can support this new information flow structure. Last but not least, further studies can also be developed to specify the detailed documentation flow from the different stakeholders to provide more detailed guidance over the involved professionals.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Cross check of co-occurrence attributes in different data structures vs. case study SAM unit data attribute

Legend:
- Project information related data attributes
- SAM Unit core information related data attributes
- Building component identification data attributes
- SAM Unit non-core data attributes (including specifications and comments)
- Building component geographic data attributes
- BIM integratable data attributes
- Other useful data attributes
- Data attribute name in COBie
- Becerik-Gerber's data structure of nongeometric data requirements
- Stride Treglown's data attribute name in UWE project
- Data attribute with less than 70% data entries
- Data attribute with more than 70% data entries

Data attribute name In SAM data model	Data attribute name in COBie	Becerik-Gerber's data structure of nongeometric data requirements	Stride Treglown's data attribute name in UWE project
Project	Project Name		
Project Type			
Site	Site Name	Site	Building
Zone	Space	Zone	
Floor Level	Floor Name	Floor	Floor
Room Type	Space Names	Room	Room Ref
Latitude	Coordinate X Axis		
Longitude	Coordinate Y Axis		
Asset ID	Tag Number	Asset ID	
Reference No.	ExtIdentifier		Unique Ref
Element Type Reference	Category		
Element Type Description Read Only	Name; Description	Asset Name	
Serial Number	Serial Number	Serial Number	Manufacturers serial no.
Model Number	Model Number	Model	Model number
Asset Code	AssetIdentifier		
Grade			Component condition
Unit Of Measure Reference	Unit	Unit	
Quantity			
Percentage Of Replacement			
Budget Cost	Value; ReplacementCost	Value	
Residual Life			
Activity Cycle			Years life expectancy
Type	Name & Description	Type	Equipment Description
BCIS Code	Category	Organizational Specific Categories	Uniclass
Year Installed	InstallationDate	Acquisition Date	Refurbishment Date
Base Costs	Impact		Replacement cost
Adjustment Factor			
Natural Replacement Or Handback			
Manufacturer	Manufacturer	Manufacturer	Manufacturer
Action Required Reference	JobType		
Health And Safety Issue	ImpactType		
Frequency In Year	Frequency		
Maintenance Issue			
Cost Source			
Lifetime Source			
Date Inspected			
Surveyor	CreatedBy		
Failure Type Reference			
SAM Comments			
Material	Material		
Additional Info	File		
Barcode	BarCode		BarCode Ref
Colour	Colour		
Size	Size		
Survey Section Reference No.			
Survey Section Name Read Only			
Element Type Name Read Only			
Element Type Composition Path Read Only			Sub-component of equipment
Priority			
Method Of Measurement Reference			
Is Complete	Stage		
Building Defect			
Existing Element			
Net LCC			
KKCost LCC			
Base Costs2			
Net LCC3			
Access Reference			
Contributing Factor Reference			
External UUID			
Accent Colour			
Finish Notes			
Surveyors Comments	Description	Description	

Appendix B. An example contractor's category list

Item Code	Item Name
1.1	Air Handling Unit (Supply and Extract)
1.2	Air Conditioning Units
1.3	Refrigeration Plant
1.4	Split Air Conditioning Units
1.5	Mortuary Refrigeration Body Stores
1.6	Electric Traction Drive Passenger and Goods Lifts
1.7	Hydraulic Drive Passenger and Goods Lifts
1.8	Pressurization Units
1.9	Pumps
1.10	Domestic Hot Water and Heating Vessels
1.11	Domestic Hot Water Mixing Valves
1.12	Heating and Cooling Pipe Work Distribution Systems
1.13	Steam Distribution and Condensate Systems
1.14	Steam Generators
1.15	Hydrotherapy Pool Treatment Plant
1.16	Water Treatment Plants
1.17	Air and Vacuum Plants
1.18	Medical Gases
1.19	Control Panels Per Unit
1.20	Regeneration Trolley Control Panels Per Unit
1.21	Cold Water Storage Tanks
1.22	Building Management System (Including Central PC, Outstation Units)
1.23	Fire Alarm Installation Per System
1.24	Sprinkler Installation (Wet)
1.25	Sprinkler Installation (Dry)
1.26	Access Control Barriers
1.27	Pay, Display and Change Machines
1.28	CCTV Equipment
1.29	Security Alarms
1.30	Electronic Access Control
1.31	High and Low Voltage Switchgear Distribution
1.32	High Voltage Transformers
1.33	Low Voltage Power Outlets
1.34	Lighting
1.35	External Lighting
1.36	Emergency Lighting
1.37	Uninterruptible/Isolated Power Supply Systems
1.38	Pneumatic Air Tube Multi-Point Transport Systems
1.39	Nurse Call and Bed Head Services
1.40	Bed Pan Washers\Macerators
1.41	Lightning Protection
1.42	Roller Shutter Doors
1.43	Electric Sliding Doors
1.44	Patient Lifting Devices
1.45	Heat Recovery Installations
1.46	Compressed Air Plant
1.47	Engineering Sundries
1.48	Emergency Generators
2.1	Safety Rails Access Ladders
2.2	Rainwater Gutters
2.3	Windows per Module
2.4	External and Internal Doors
2.5	External Surfaces
2.6	Internal Walls
2.7	Internal and External Signage
2.8	Sanitary Ware
2.9	External Cladding Panels
2.10	Floor Coverings
2.11	Roofs
2.12	Ceilings
2.13	Furniture, Fixtures and Fittings
2.14	Hard Landscaping
2.15	Building Surfaces
2.16	Impact Resistant Coverings
2.17	Door Locks and Keeps
2.18	Ward Based Medical Furniture
2.19	Theatre Medical Furniture
2.20	Hydrotherapy Pools
2.21	Stair and Hand Rails
2.22	Building Sundries
2.23	Soft Landscaping
3.1	Bratt Pans (Gas)
3.2	Boiling Kettles (Steam)
3.3	Gas Hob Over Convection Ovens

(*continued*)

Item Code	Item Name
3.4	Solid Top Oven Ranges
3.5	Cryogenic Chillers
3.6	Electro Mechanical Blast Chillers
3.7	Flight Dishwashers
3.8	Utensil Washer
3.9	Food Storage Cold Rooms
3.10	Tray Conveyors
3.11	Rotary Reel Oven
3.12	Fan Convector Ovens
3.13	Waste Disposal Units
3.14	Heated Food Cabinets
3.15	Deep Fat Fryers

Appendix C. A hierarchical BIM-integrated portfolio-based SAM data attribute structure (detailed)

1st Priority
- Project Information related data attributes
- SAM Unit core information related data attributes
- Building component identification data attributes

2nd Priority
- Health and Safety (other legally Risky) data attributes
- SAM Unit non-core data attributes (including specifications and comments)
- External Project Information

3rd Priority
- Building component geographic data attributes
- BIM integratable data attributes
- Other useful data attributes
- Externality and Sustainable Data Attributes

- ID & Name
- Service Zone
- Group and Type
- Manufacturer/Vendor Data
- Specifications and Attributes
- Operation and Maintenance Data
- Authorization
- Revit Compulsory Element

Project SAM Unit Data Group	Data Attributes in Becerik-Gerber's Data Groups	Data Attributes Combined	Data Attributes In Existing SAM Data Model	Data Attributes in Becerik-Gerber's Data Structure	Data Attributes in COBie Sample Spreadsheet	Data Attributes in UWE
Project information related data attributes	Service Zone	Project Type	Project Type			Discipline
Project information related data attributes	Service Zone	Project	Project			Campus
Project information related data attributes	Service Zone	Site	Site	Site	Site Name	Building
Project information related data attributes	Service Zone	Building		Building		
Project information related data attributes	Service Zone	Floor	Floor Level	Floor	Floor Name	Floor
Project information related data attributes	Service Zone	Room	Room Type	Room	Space Names	Room Ref
Project information related data attributes	Service Zone	Zone	Zone	Zone	Name (Zone name)	
Project information related data attributes	Service Zone	UsableHeight			Usable Height	
SAM Unit core information related data attributes	Manufacturer/Vendor Data	Manufacturer	Manufacturer	Manufacturer	Manufacturer	Manufacturer
SAM Unit core information related data attributes	Manufacturer/Vendor Data	Vendor		Vendor	Suppliers	
SAM Unit core information related data attributes	Manufacturer/Vendor Data	Warranty Expiration		Warranty Expiration		
SAM Unit core information related data attributes	Manufacturer/Vendor Data	Warranty Guarantor Parts			Warranty Guarantor Parts	
SAM Unit core information related data attributes	Manufacturer/Vendor Data	Warranty Duration Parts			Warranty Duration Parts	Warranty Duration Parts
SAM Unit core information related data attributes	Manufacturer/Vendor Data	Warranty Guarantor Labor			Warranty Guarantor Labor	
SAM Unit core information related data attributes	Manufacturer/Vendor Data	Warranty Duration Labor			Warranty Duration Labor	Warranty Duration Labor
SAM Unit core information related data attributes	Manufacturer/Vendor Data	Warranty Start Date			Warranty Start Date	Commissioning date / Warranty
SAM Unit core information related data attributes	Specifications and Attributes	Quantity	Quantity			
SAM Unit core information related data attributes	Specifications and Attributes	Base Cost (Value)	Base Cost / Budget Cost	Value	Value (Impact) (or ReplacementCost)	
SAM Unit core information related data attributes	Specifications and Attributes	Material	Material		Material	
SAM Unit core information related data attributes	Operation and Maintenance Data	ReplacementCost (Budget Cost)	Budget Cost (Duplicated)		Replacement Cost	
SAM Unit core information related data attributes	Operation and Maintenance Data	Expected Life	Activity Cycle		Expected Life	Years life expectancy
SAM Unit core information related data attributes	Operation and Maintenance Data	Frequency	Frequency In Year		Frequency	
SAM Unit core information related data attributes	Operation and Maintenance Data	Grade	Grade			Component condition
SAM Unit core information related data attributes	Operation and Maintenance Data	Percentage Of Replacement	Percentage Of Replacement			
SAM Unit core information related data attributes	Operation and Maintenance Data	Adjustment Factor	Adjustment Factor			
SAM Unit core information related data attributes	Operation and Maintenance Data	Natural Replacement Or Handback	Natural Replacement Or Handback			
SAM Unit core information related data attributes	Operation and Maintenance Data	Maintenance Issue	Maintenance Issue			
SAM Unit core information related data attributes	Operation and Maintenance Data	Date Inspected	Date Inspected			
SAM Unit core information related data attributes	Operation and Maintenance Data	Failure Type Reference	Failure Type Reference			
Building component identification data attributes	ID & Name	Asset ID		Asset ID	UID	
Building component identification data attributes	ID & Name	Asset Name		Asset Name	Name (Type); JobType	
Building component identification data attributes	ID & Name	Name (Component)	Element Type Description Read Only		Name (Component)	
Building component identification data attributes	ID & Name	Name (System)			Name (System)	
Building component identification data attributes	Group and Type	Uniformat Name (System)	BCIS Code	Uniformat		Uniclass
Building component identification data attributes	Group and Type	Organizational Specific Categories	Element Type Reference	Organizational Specific Categories	Category	
Building component identification data attributes	Specifications and Attributes	Unit	Unit Of Measure	Unit	Unit	
Health and Safety (other legally Risky) data attributes	Specifications and Attributes	Grade (e.g. Highly vandal resistant)			Grade (e.g. Highly vandal resistant)	Equipment Standard (Non BIM only); Fire Rating
Health and Safety (other legally Risky) data attributes	Specifications and Attributes	Constituents			Constituents	
Health and Safety (other legally Risky) data attributes	Specifications and Attributes	Type (Issue)			Type (Issue)	
Health and Safety (other legally Risky) data attributes	Operation and Maintenance Data	Risk			Risk	
SAM Unit non-core data attributes (including specifications and comments)	Operation and Maintenance Data	Spare Parts		Spare Parts		
SAM Unit non-core data attributes (including specifications and comments)	Operation and Maintenance Data	Lead In Time			Lead In Time	
SAM Unit non-core data attributes (including specifications and comments)	Operation and Maintenance Data	Lead Out Time	Project Type		Lead Out Time	Discipline
SAM Unit non-core data attributes (including specifications and comments)	Operation and Maintenance Data	File (e.g. hyperlink or file name)	Additional Info		File (e.g. hyperlink or file name)	O&M information (hyperlink to relevant page)
SAM Unit non-core data attributes (including specifications and comments)	Operation and Maintenance Data	SAM Comments	SAM Comments			
SAM Unit non-core data attributes (including specifications and comments)	Operation and Maintenance Data	Surveyors Comments	Surveyors Comments			
SAM Unit non-core data attributes (including specifications and comments)	Manufacturer/Vendor Data	Model Number	ModelNumber	Model	Model Number	Model Number
SAM Unit non-core data attributes (including specifications and comments)	Manufacturer/Vendor Data	Serial Number	Serial Number	Serial Number	Serial Number	Manufacturers serial no.
SAM Unit non-core data attributes (including specifications and comments)	Manufacturer/Vendor Data	Tag Number	Asset ID		Tag Number	
SAM Unit non-core data attributes (including specifications and comments)	Specifications and Attributes	Description (Type)	Type	Type	Description	Equipment Description
SAM Unit non-core data attributes (including specifications and comments)	Specifications and Attributes	Cost Source	Cost Source			
SAM Unit non-core data attributes (including specifications and comments)	Specifications and Attributes	Lifetime Source	Lifetime Source			
SAM Unit non-core data attributes (including specifications and comments)	Specifications and Attributes	Description		Description		
SAM Unit non-core data attributes (including specifications and comments)	Specifications and Attributes	Colour	Colour		Colour	
SAM Unit non-core data attributes (including specifications and comments)	Specifications and Attributes	Finish			Finish	
External Project Information	Specifications and Attributes	Owner			Owner	
External Project Information	Manufacturer/Vendor Data	Service Contract duration				Service Contract duration
External Project Information	ID & Name	Project Description			Project Description	
External Project Information	ID & Name	Site Description			Site Description	
External Project Information	ID & Name	Phase			Phase	
External Project Information	Service Zone	Linear Units			Linear Units	
External Project Information	Service Zone	Area Units			Area Units	
External Project Information	Service Zone	Volume Units			Volume Units	
External Project Information	Service Zone	Currency Unit			Currency Unit	
External Project Information	Service Zone	Area Measurement			Area Measurement	
External Project Information	Service Zone	Elevation			Elevation	
External Project Information	Service Zone	Gross Area			Gross Area	
External Project Information	Service Zone	Net Area			Net Area	
Building component geographic data attributes	Specifications and Attributes	Coordinate X Axis	Latitude		Coordinate X Axis	
Building component geographic data attributes	Specifications and Attributes	Coordinate Y Axis	Longitude		Coordinate Y Axis	
Building component geographic data attributes	Specifications and Attributes	Coordinate Z Axis			Coordinate Z Axis	
BIM integratable data attributes	Manufacturer/Vendor Data	BarCode	BarCode		BarCode	Barcode Ref
BIM integratable data attributes	Manufacturer/Vendor Data	Asset Identifier	AssetCode		Asset Identifier	
BIM integratable data attributes	Revit Compulsory Element	ExtObject			ExtObject	
BIM integratable data attributes	Revit Compulsory Element	ExtIdentifier	Reference No.		ExtIdentifier	Unique Ref
Other useful attributes	Authorization	Created By	Surveyor		Created By	
Other useful attributes	Authorization	Created On			Created On	
Other useful attributes	Operation and Maintenance Data	Approval By			Approval By	
Other useful attributes	Operation and Maintenance Data	SFG20 planned Maintenance Scheduling				SFG20 planned Maintenance Scheduling
Externality and Sustainable Data Attributes	Operation and Maintenance Data	Accessibility Performance			Accessibility Performance	
Externality and Sustainable Data Attributes	Operation and Maintenance Data	Impact Type	Health And Safety Issue		Impact Type	
Externality and Sustainable Data Attributes	Operation and Maintenance Data	Duration (Impact)			Duration (Impact)	
Externality and Sustainable Data Attributes	Operation and Maintenance Data	Chance			Chance	
Externality and Sustainable Data Attributes	Operation and Maintenance Data	Impact	Base Costs		Impact	Replacement cost
Externality and Sustainable Data Attributes	Specifications and Attributes	Power		Power		Power
Externality and Sustainable Data Attributes	Specifications and Attributes	Energy Consumption		Energy Consumption		
Externality and Sustainable Data Attributes	Specifications and Attributes	SustainabilityPerformance			SustainabilityPerformance	

References

[1] B. Becerik-Gerber, F. Jazizadeh, N. Li, G. Calis, Application areas and data requirements for BIM-enabled facilities management, J. Constr. Eng. Manag. 138 (3) (2012) 431–442, https://doi.org/10.1061/(asce)co.1943-7862.0000433.

[2] R. Eadie, M. Browne, H. Odeyinka, C. McKeown, S. McNiff, BIM implementation throughout the UK construction project lifecycle: an analysis, Autom. Constr. 36 (2013) 145–151, https://doi.org/10.1016/j.autcon.2013.09.001.

[3] P. Pishdad-Bozorgi, X. Gao, C. Eastman, A.P. Self, Planning and developing facility management-enabled building information model (FM-enabled BIM), Autom. Constr. 87 (2018) 22–38, https://doi.org/10.1016/j.autcon.2017.12.004.

[4] M. Kassem, G. Kelly, N. Dawood, M. Serginson, S. Lockley, BIM in facilities management applications: a case study of a large university complex, Built Environ. Project Asset Manag. 5 (3) (2015) 261–277, https://doi.org/10.1108/bepam-02-2014-0011.

[5] E. William East, N. Nisbet, T. Liebich, Facility management handover model view, J. Comput. Civ. Eng. 27 (1) (2013) 61–67, https://doi.org/10.1061/(asce)cp.1943-5487.0000196.

[6] M.G. Kaiser, F. El Arbi, F. Ahlemann, Successful project portfolio management beyond project selection techniques: understanding the role of structural alignment, Int. J. Proj. Manag. 33 (1) (2015) 126–139, https://doi.org/10.1016/j.ijproman.2014.03.002.

[7] T.W. Kang, C.H. Hong, A study on software architecture for effective BIM/GIS-based facility management data integration, Autom. Constr. 54 (2015) 25–38, https://doi.org/10.1016/j.autcon.2015.03.019.

[8] E.A. Pärn, D.J. Edwards, M.C. Sing, The building information modelling trajectory in facilities management: a review, Autom. Constr. 75 (2017) 45–55, https://doi.org/10.1016/j.autcon.2016.12.003.

[9] I.O.f. Standardization, ISO 55000: Asset Management-Overview, Principles and Terminology, International Organization for Standardization. https://www.iso.org/standard/55088.html, 2014 (accessed August 19, 2021).

[10] R.M.W. Horner, M. El-Haram, A. Munns, Building maintenance strategy: a new management approach, J. Qual. Maint. Eng. 3 (4) (1997) 273–280, https://doi.org/10.1108/13552519710176881.

[11] D. Jonas, A. Kock, H.G. Gemünden, Predicting project portfolio success by measuring management quality—a longitudinal study, IEEE Trans. Eng. Manag. 60 (2) (2012) 215–226, https://doi.org/10.1109/tem.2012.2200041.

[12] M. Voss, A. Kock, Impact of relationship value on project portfolio success—investigating the moderating effects of portfolio characteristics and external turbulence, Int. J. Proj. Manag. 31 (6) (2013) 847–861, https://doi.org/10.1016/j.ijproman.2012.11.005.

[13] R. Edirisinghe, K.A. London, P. Kalutara, G. Aranda-Mena, Building information modelling for facility management: are we there yet? Eng. Constr. Archit. Manag. 24 (2017) 1119–1154, https://doi.org/10.1108/ecam-06-2016-0139.

[14] A. Alnaggar, M. Pitt, Towards a conceptual framework to manage BIM/COBie asset data using a standard project management methodology, J. Facil. Manag. 17 (2) (2019) 175–187, https://doi.org/10.1108/jfm-03-2018-0015.

[15] M. Chu, J. Matthews, P.E.D. Love, Integrating mobile building information modelling and augmented reality systems: an experimental study, Autom. Constr. 85 (2018) 305–316, https://doi.org/10.1016/j.autcon.2017.10.032.

[16] R. Jin, C. Hancock, L. Tang, C. Chen, D. Wanatowski, L. Yang, Empirical study of BIM implementation–based perceptions among Chinese practitioners, J. Manag. Eng. 33 (2017) 4017025, https://doi.org/10.1061/(asce)me.1943-5479.0000538.

[17] P.M. Teicholz, BIM for Facility Managers, Hoboken, John Wiley & Sons, Inc., New Jersey, 2013. ISBN1118382811.

[18] R.G. Cooper, S.J. Edgett, E.J. Kleinschmidt, Portfolio management in new product development: lessons from the leaders—I, Res. Technol. Manag. 40 (5) (1997) 16–28, https://doi.org/10.1080/08956308.1997.11671152.

[19] J. Teller, A. Kock, An empirical investigation on how portfolio risk management influences project portfolio success, Int. J. Proj. Manag. 31 (6) (2013) 817–829, https://doi.org/10.1016/j.ijproman.2012.11.012.

[20] R. Kangari, L. Riggs, Portfolio management in construction, Constr. Manag. Econ. 6 (2) (1988) 161–169, https://doi.org/10.1080/01446198800000014.

[21] RICS, Infrastructure Management: Current Practices and Future Trends. http://www.rics.org/nz/knowledge/research/insights/infrastructure-management-current-future/, 2017. (Accessed 18 August 2021).

[22] M.S. Valen, N.O. Olsson, Are we heading towards mature facilities management in Norwegian municipalities? J. Facil. Manag. 10 (4) (2012) 287–300, https://doi.org/10.1108/14725961211265747.

[23] N. Madhusanka, M.M. Kumaraswamy, W. Pan, S.Y. Chan, Relationally integrated value networks for total asset management in project portfolios, Infrastruct. Asset Manag. (2020) 1–12, https://doi.org/10.1680/jinam.19.00059.

[24] A.N. Gade, T.S. Larsen, S.B. Nissen, R.L. Jensen, REDIS: a value-based decision support tool for renovation of building portfolios, Build. Environ. 142 (2018) 107–118, https://doi.org/10.1016/j.buildenv.2018.06.016.

[25] J. McArthur, C. Jofeh, Portfolio retrofit evaluation: a methodology for optimizing a large number of building retrofits to achieve triple-bottom-line objectives, Sustain. Cities Soc. 27 (2016) 263–274, https://doi.org/10.1016/j.scs.2016.03.011.

[26] F. Farzan, S.A. Vaghefi, K. Mahani, M.A. Jafari, J. Gong, Operational planning for multi-building portfolio in an uncertain energy market, Energy Build. 103 (2015) 271–283, https://doi.org/10.1016/j.enbuild.2015.06.060.

[27] R.G. Cooper, S.J. Edgett, E.J. Kleinschmidt, Portfolio Management for New Products, 2001. ISBN0738205141.

[28] C. Benko, F.W. McFarlan, W.F. McFarlan, Connecting the Dots: Aligning Projects with Objectives in Unpredictable Times, Harvard Business Press, 2003. ISBN1578518776.

[29] M. Martinsuo, P. Lehtonen, Role of single-project management in achieving portfolio management efficiency, Int. J. Proj. Manag. 25 (1) (2007) 56–65, https://doi.org/10.1016/j.ijproman.2006.04.002.

[30] C.P. Killen, R.A. Hunt, Dynamic capability through project portfolio management in service and manufacturing industries, Int. J. Manag. Proj. Bus. 3 (1) (2010) 157–169, https://doi.org/10.1108/17538371011014062.

[31] J. Teller, B.N. Unger, A. Kock, H.G. Gemünden, Formalization of project portfolio management: the moderating role of project portfolio complexity, Int. J. Proj. Manag. 30 (5) (2012) 596–607, https://doi.org/10.1016/j.ijproman.2012.01.020.

[32] B.N. Unger, A. Kock, H.G. Gemünden, D. Jonas, Enforcing strategic fit of project portfolios by project termination: an empirical study on senior management involvement, Int. J. Proj. Manag. 30 (6) (2012) 675–685, https://doi.org/10.1016/j.ijproman.2011.12.002.

[33] M. Martinsuo, J. Geraldi, Management of project portfolios: relationships of project portfolios with their contexts, Int. J. Proj. Manag. 38 (7) (2020) 441–453, https://doi.org/10.1016/j.ijproman.2020.02.002.

[34] C.P. Killen, Managing portfolio interdependencies: the effects of visual data representations on project portfolio decision making, Int. J. Manag. Proj. Bus. 10 (4) (2017) 856–879, https://doi.org/10.1108/ijmpb-01-2017-0003.

[35] S. Elonen, K.A. Artto, Problems in managing internal development projects in multi-project environments, Int. J. Proj. Manag. 21 (6) (2003) 395–402, https://doi.org/10.1016/s0263-7863(02)00097-2.

[36] F. Ghasemi, M.H.M. Sari, V. Yousefi, R. Falsafi, J. Tamošaitienė, Project portfolio risk identification and analysis, considering project risk interactions and using Bayesian networks, Sustainability 10 (5) (2018) 1609, https://doi.org/10.3390/su10051609.

[37] A.V. Levitin, T.C. Redman, Data as a resource: properties, implications, and prescriptions, MIT Sloan Manag. Rev. 40 (1) (1998) 89. https://sloanreview.mit.edu/article/data-as-a-resource-properties-implications-and-prescriptions/ (accessed August 18, 2021).

[38] R.Y. Wang, D.M. Strong, Beyond accuracy: what data quality means to data consumers, J. Manag. Inf. Syst. 12 (4) (1996) 5–33, https://doi.org/10.1080/07421222.1996.11518099.

[39] G.I. Kendall, S.C. Rollins, Advanced Project Portfolio Management and the PMO: Multiplying ROI at Warp Speed, J. Ross Publishing, 2003. ISBN1932159029.

[40] S. Lin, J. Gao, A. Koronios, A data quality framework for engineering asset management, Engineering Asset Management, Springer, 2006, pp. 473–482, https://doi.org/10.1007/978-1-84628-814-2_51.

[41] S. Watts, G. Shankaranarayanan, A. Even, Data quality assessment in context: a cognitive perspective, Decis. Support. Syst. 48 (1) (2009) 202–211, https://doi.org/10.1016/j.dss.2009.07.012.

[42] Audit Commission, Improving Information to Support Decision Making: Standards for Better Quality Data. https://lemosandcrane.co.uk/resources/AC%20-%20Improving%20information%20to%20support%20decisionmaking.pdf, 2007.

[43] M.F. Uddin, N. Gupta, Seven V's of Big Data understanding Big Data to extract value: Proceedings of the 2014 zone 1 conference of the American Society for Engineering Education, IEEE, 2014, pp. 1–5, https://doi.org/10.1109/aseezone1.2014.6820689.

[44] L. Cai, Y. Zhu, The challenges of data quality and data quality assessment in the big data era, Data Sci. J. 14 (2015), https://doi.org/10.5334/dsj-2015-002.

[45] B. Heinrich, D. Hristova, M. Klier, A. Schiller, M. Szubartowicz, Requirements for data quality metrics, J. Data Inform. Quality (JDIQ) 9 (2) (2018) 1–32, https://doi.org/10.1145/3148238.

[46] P.A. Zadeh, G. Wang, H.B. Cavka, S. Staub-French, R. Pottinger, Information quality assessment for facility management, Adv. Eng. Inform. 33 (2017) 181–205, https://doi.org/10.1016/j.aei.2017.06.003.

[47] Y. Jung, M. Joo, Building information modelling (BIM) framework for practical implementation, Autom. Constr. 20 (2) (2011) 126–133, https://doi.org/10.1016/j.autcon.2010.09.010.

[48] K. Chen, W. Lu, Y. Peng, S. Rowlinson, G.Q. Huang, Bridging BIM and building: from a literature review to an integrated conceptual framework, Int. J. Proj. Manag. 33 (6) (2015) 1405–1416, https://doi.org/10.1016/j.ijproman.2015.03.006.

[49] N. Gu, K. London, Understanding and facilitating BIM adoption in the AEC industry, Autom. Constr. 19 (8) (2010) 988–999, https://doi.org/10.1016/j.autcon.2010.09.002.

[50] B. Succar, Building information modelling framework: a research and delivery foundation for industry stakeholders, Autom. Constr. 18 (3) (2009) 357–375, https://doi.org/10.1016/j.autcon.2008.10.003.

[51] P.E. Love, J. Matthews, I. Simpson, A. Hill, O.A. Olatunji, A benefits realization management building information modeling framework for asset owners, Autom. Constr. 37 (2014) 1–10, https://doi.org/10.1016/j.autcon.2013.09.007.

[52] B. Dave, A. Buda, A. Nurminen, K. Främling, A framework for integrating BIM and IoT through open standards, Autom. Constr. 95 (2018) 35–45, https://doi.org/10.1016/j.autcon.2018.07.022.

[53] Stride Treglown, LINKING BIM TO CAFM Turning Asset Data into Knowledge. https://www.ciobacademy.org/wp-content/uploads/2017/07/MFTG.pdf, 2017 (accessed August 19, 2021).

[54] BSI, PAS 1192–2:2013 Specification for information management for the capital/delivery phase of construction projects using building information modelling, BSI Standards Publication, 2013 https://doi.org/Published by the British Standard Institute. British Standard Limited. ISSN9780580781360.

[55] M. Munir, A. Kiviniemi, S.W. Jones, Business value of integrated BIM-based asset management, Eng. Constr. Archit. Manag. 26 (6) (2019) 1171–1191, https://doi.org/10.1108/ecam-03-2018-0105.

[56] R. Santos, A.A. Costa, J.D. Silvestre, L. Pyl, Integration of LCA and LCC analysis within a BIM-based environment, Autom. Constr. 103 (2019) 127–149, https://doi.org/10.1016/j.autcon.2019.02.011.

[57] P. Pishdad-Bozorgi, X. Gao, C. Eastman, A.P. Self, Planning and developing facility management-enabled building information model (FM-enabled BIM), Autom. Constr. 87 (2018) 22–38, https://doi.org/10.1016/j.autcon.2017.12.004.

[58] M. Kassem, G. Kelly, N. Dawood, M. Serginson, S. Lockley, BIM in facilities management applications: a case study of a large university complex, Built Environ. Project Asset Manag. 5 (3) (2015) 261–277, https://doi.org/10.1108/bepam-02-2014-0011.