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# Lean Management Framework for Healthcare Facilities Integrating BIM, BEPS and Big Data Analytics

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**Abstract:** An increase in the usage of information and communication technologies (ICT) and the Internet of Things (IoT) in Facility Management (FM) induces a huge data stack. Even though these data bring opportunities such as cost savings, time savings, increase in user comfort, space optimization, energy savings, inventory management, etc., these data sources cannot be managed and manipulated effectively to increase efficiency at the FM stage. In addition to data management issues, FM practices, or developed solutions, need to be supported with the implementation of lean management philosophy to reveal organizational and managerial wastes. In the literature, some researchers performed studies about awareness about building information modeling (BIM)-FM, and FM-related data management problems in terms of lean philosophy. However, the comprehensive solution for effective FM has not been investigated with the application of lean management philosophy yet. Therefore, this study aims to develop an FM framework for healthcare facilities by considering lean management philosophy since more stable workflow, continuous improvement, and creating more value to customers will help to deliver a more acceptable solution for the FM industry. Within this context, the integration of BIM, Building Energy Performance Simulations, and Big Data Analytics are proposed as a solution. In the study, the Design Science Research (DSR) methodology was followed to develop the FM framework. Depending on the DSR methodology, two scenarios were used to investigate the issue in a real healthcare facility and develop the FM framework. The developed framework was evaluated by four experts, and the revisions of the proposed framework were realized.

**Keywords:** Building Information Modeling (BIM); Building Energy Performance Simulations (BEPS); Big Data Analytics (BDA)

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## 1. Introduction

Facility Management (FM) has a considerable share in nations' economies. It is such that the annual turnover of FM companies and FM support services has reached GBP 115 bn in the United Kingdom [1]. The comparison of OPEX (operational expenditures) with CAPEX (capital expenditures) showed that OPEX, which corresponds to the facility management (FM) stage, is the most costly stage [2,3]. The main reason for this is that there is no right strategy and decision-making approach in facility management.

Nowadays, data availability depending on digital transformation in the Architecture, Engineering, and Construction (AEC) industry, has increased rapidly. The usage of available data is essential to eliminate inefficiency in FM. However, data-related issues in FM induces the implementation of inefficient decisions and processes due to "inconsistent naming, formatting, and storage of data, insufficient or overwhelming volumes of data, unreliable data needing validation due to errors or obsolescence, incomplete or obscured information, unavailable information, irrelevant information" [4]. Furthermore, these types of information issues cause inefficiencies, such as labor hours to find accurate information from a data stack or data retrieval multiple times from facilities [4].

Chen et al. (2018) reported that facility maintenance is the main portion of expenditure of facility management with 65%. Furthermore, maintenance activities affect other FM areas [5]. For instance, abnormal faults in Heating, Cooling, Ventilating and Air Conditioning (HVAC) can result in decreased energy efficiency and unnecessary energy waste [6]. In maintenance management, delays, rework, disruption of services, and over-resource allocation are other issues due to the unpredicted nature of maintenance issues [7,8]. Furthermore, shutdowns or outages in facilities cause to stop in production or giving a service process [9]. Depending on available data, fault detection and diagnosis can be performed to identify faults in the system operation to eliminate more energy consumption or more severe problems in the facility [10].

Energy consumption of buildings constitutes a substantial part of national energy consumption [4]. Additionally, HVAC, which is used in facilities, has over 30% energy consumption in the total energy consumption of the World. With effective energy management, such as thermostat operation mode, etc., energy savings can be enabled in the facilities [10]. Furthermore, energy consumption in the buildings has a direct effect on $CO_2$ emission. Therefore, energy consumption needs to be controlled and observed within the facilities. Moreover, legal obligations for net-zero carbon emissions in public facilities and dwellings such as the UK force the development of energy management strategies [11].

As a result of the above inefficiencies, the existing literature emphasizes that process and operational activities in FM need to be improved and replaced with more efficient and effective lean FM activities [12]. Within this context, Lean Management Philosophy (LMP) in FM can provide an opportunity to improve the low productivity [13]. LMP can be applied to organize and manage processes and activities with more efficient activities and processes by reducing wastes and increasing value to the customers [12]. Furthermore, LMP helps to improve collaboration, cost performance, schedule performance, construction safety, environmental impacts, enhance the sustainable development idea, the flow of information and handling material, improving productivity, quality and customer satisfaction [13–15].

However, the LMP implementations in the FM stage are not the intended level since four issues induce inefficiency and wastes in FM according to the observations from industry applications that were performed during this study. Firstly, the most important issue of FM practitioners is to achieve necessary data resources such as energy data, maintenance data, as-built data, etc. The practitioners believed that the issue depends on the lack of the requirements of facility management practices into the design stage. Secondly, the evaluation or interpretation of the existing data sources to achieve lean practices in FM is not clearly understood and implemented. Thirdly, the reporting and tracking of performed activities are one of the sources of inefficiencies in FM. Fourthly, the lack of visualization technologies in FM induces inefficiencies since visual perception plays an important role in conceiving building components and the environment in FM. Therefore, the FM needs to be supported with the help of new technologies.

Within this context, in the literature, building information modeling (BIM)-FM studies showed that BIM could be used in real-time data and its visualization, maintainability, data collection, energy consumption monitoring, space management, retrofitting, problem-solving, productivity, efficiency and less time to respond to problems, reduced data re-entry, data management, proactive maintenance, emergency management, asset data, up to date model, interoperability of data within the different platforms, maintenance costs, locating building components, considering and updating digital assets, warranty and service information and provided a more controllable environment in FM [2,16–21]. Besides this, the FM systems only provide data and information. However, the conversion of this information into knowledge and using this knowledge in the FM process are possible with new concepts. To overcome productivity and to improve the decision-making process, the use of Big Data

Analytics (BDA) needs to be applied in FM because the volume and variety of asset management data necessitate data analytics [12,22,23]. Therefore, BIM-BDA integrated solutions for FM are critical to solving issues.

Although there are the existing framework and developed solutions, including BIM, BIM-BEPS (building energy performance simulations), and BIM-BDA, these frameworks and solutions focus on specific FM issues such as energy management, maintenance, emergency management and data query. However, they fell short in considering all perspectives of FM and their organizational development and implementation aspects. Furthermore, the focus on only one area in FM induces another inefficiency or waste in terms of usage of different FM software in a facility. Thus, significant data relationships cannot be discovered to improve FM. Therefore, it is believed that the consideration of LMP and all FM perspectives in the developed FM solutions or platforms help to eliminate not only data-driven wastes but also organizational and managerial issues. Furthermore, existing studies about BIM-LC-FM focused on either the increase in awareness about BIM and FM in terms of lean philosophy or confronted issues when performing BIM usage in FM in terms of data management. Therefore, to address the above FM issues, inefficiencies, wastes, etc., this study aims to develop an FM framework with an Information Delivery Manual (IDM) in which reduced wastes and variability are provided for healthcare facilities by considering LMP. In the study, three questions are explored, namely:

1. Can the Lean approach help for the integrated use of BIM, BEPS and Big Data Analytics for effective Healthcare Facilities Management?
2. What are the synergies between Healthcare FM and the Lean thinking concept?
3. Can the integrated use of BIM, BEPS and Big Data Analytics enable the Lean concept in healthcare FM?

This study contributes to theoretical critics in FM literature, developing an integrated FM framework for healthcare facilities by considering LMP. Additionally, except for available FM solutions, this study illustrates which technologies and disciplines need to be considered. With expert views, the study contributes to the practice with the proposed FM framework that includes which processes need to be found in the FM. The research also shows how clients/end-users need to assess the FM platform to implement lean practices in FM.

## 2. Literature Review

New high-tech systems are finding more application areas in facilities. In the future, the facilities will require learning systems and automated systems [24]. To achieve this, FM systems need to be more expandable and offer data analytics opportunities. In the literature, Building Energy Management Systems (BEMS), Building Automation Systems (BAS), and Computerized Maintenance Management Systems (CMMS), etc. have been used as an FM system. However, there are some issues in the usage of these systems. Some of them are highly dependent on sensors [25], challenges in the new scenario implementations and extensions of sensors [25], collecting and recording limited information in their systems [26], predefined operation strategies such as set-points (decrease in energy efficiency—between 10–15%) [27,28], a huge data stack [29], low monitoring capacity due to dependence on controlling and automation process [10], missing or erroneous data due to sensor issues [30] and a lack of data analytics or limited data analytics in CMMS, BAS, BEMS, security systems and Computer-Aided Facility Management (CAFM) [31]. Additionally, some organizational and management expectations from these technologies such as FM staff, the integration of existing data in FM processes, etc. are missing in FM software. These issues not only induce inefficiencies and wastes in the management of facilities but also disrepute for FM software. Therefore, it is believed that considering LMP in FM will increase efficiency.

As a consequence, the above restrictions for FM systems, the necessity of usage data which comes from design and construction stage, heterogeneous data, IoT related issues, and storage issues in BIM lead to the consideration of the integration of BIM, Building Energy Performance Simulations and BDA within the study [32,33]. Figure 1 shows the scope of the FM data management framework required in FM.

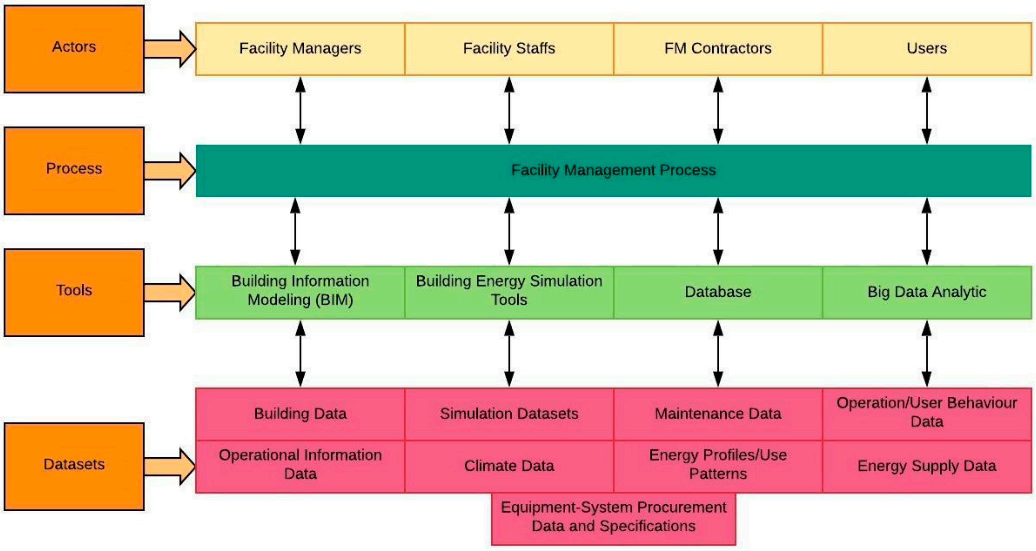


**Figure 1.** Facility Management (FM) data management vision (adopted from [34]).

Therefore, the related literature review about BIM-BDA is summarized in this section.

*2.1. Building Information Modeling*

BIM can be used to enable a single management resource for FM. Furthermore, it is believed that BIM is a promising tool due to its capacity to reduce facility managers' tasks and data extraction for facility management. However, this only helps to query data in BIM, since BIM only helps to monitor or store data. Thus, the usage of BIM induces us not to consider continuous improvement in the FM. Therefore, a data-driven decision with the usage of available data in BIM can be only possible with the data analytics. Therefore, BIM integrated FM is in its infancy. However, BIM-FM can be performed in modeling and managing energy, access to and integration of maintenance information and knowledge achieving as-built information, achieving details of warranty and service, assessment and monitoring, space managing, emergency management, retrofit planning, the provision of feedback to eliminate design-related performance issues, achieving digital asset with real-time data access and safety management. Therefore, problem-solving, productivity, efficiency, less time to respond to problems, reduced data re-entry, data management, decrease maintenance costs, proactive maintenance, locating building components, LCA analysis, indoor navigation, marketing, data management, personnel training, controlling lifecycle cost data, controlling lifecycle environmental data, real-time integrated building, maintenance and management data, maintainability, space management, efficient planning and feasibility studies for non-capital construction, personnel training, expediting search and rescue and visualization can be performed with BIM [16,18,19,21,35–40].

However, the data that is found in the BIM model needs to be analyzed and used in FM processes. Otherwise, the usage of BIM in FM can be one of the wastes and the reason for the productivity losses. Therefore, before BIM and FM are integrated, the initial step must be the integration of customers or end-users in the design stage to increase value. Thus, their requirements for FM can be considered [41]. However, nowadays, the usage of the BIM model is ended at the operation, and the maintenance stage or information, which is available in the BIM model, is transferred into FM systems, and the implementation of BIM during the operation and maintenance phase is ended [42]. Furthermore, Araszkiewicz [43] stated that BIM implementation with FM systems helps to reduce manual effort to input necessary data into FM systems. Nonetheless, the data transfer between BIM and other platforms (FM systems or other BIM solutions) is not a smooth process due to the interoperability problems [44].

In the literature, the applicability of BIM in FM processes is investigated under survey and interview studies or FM software solutions. However, this study shared developed solutions for FM since survey and interview studies are out of scope. The studies were summarized in Table 1.

**Table 1.** Literature review for building information modeling (BIM)-FM studies.

| The Aim of the Studies | References |
|---|---|
| Development of VR-based BIM model for FM | [45] |
| Development of a BIM-based facility information management framework by using Unified Modeling Language (UML) | [46] |
| Development of 3D based space management visual information system for large scale airports | [47] |
| Development of schema and transformation rules to query BIM models in SQL database | [48] |
| Development of FM software architecture by the integration of BIM, GIS, and FM data | [49] |
| Development of API to convert 3D models into a queryable format | [50] |
| Development of the Building Handover Information Model (BHIM) framework by integrating BIM and Dynamo | [44] |
| The integration of Augmented Reality (AR) with BIM to improve navigation in the facility | [51] |
| The integration of AR and FM to retrieve location information | [3] |
| Development of a framework to schedule automatically work orders and to find optimal maintenance paths | [52] |
| Development of a theoretical framework by combining SCADA system, fault detection system, BIM and building performance analysis simulations for energy management | [53] |
| Development of a system that integrates BIM and BAS information automatically with the help of Dynamo/Python. | [54] |
| Integration of BIM and data mining methods to discover more energy-efficient building operations | [55] |
| Integration of BIM, building energy performance simulations (BEPS), data warehouse and sensors for energy management | [56] |
| Development of a semantic web-based FM system for maintenance management | [57] |
| Integration of BIM and GIS to overcome tunnel facility management issues such as "numerous staff and equipment, difficult to organize and manage paper document, and real-time monitoring." | [58] |
| Development of FM technology (iAERTS) by the integration of BIM and Unity platform to analyze power consumption depending on space, monitoring energy consumption, and giving tips in terms of reducing energy consumption | [59] |
| Development of a BIM plug-in tool to detect potentially damaged components in a Heating, Cooling, Ventilating, and Air Conditioning (HVAC) system | [60] |
| Development of a tool for the optimization of the energy performance of buildings through wireless sensors, actuators and BIM | [61] |

As a consequence, BIM has been investigated in terms of applicability in FM and as an FM software or part of an FM system in the literature. However, the studies showed that there is no comprehensive solution for data query and analysis of available data which is found in BIM to reveal wastes and to enable continuous improvement within building energy consumption, user behavior in buildings, emergency and safety management in buildings, operation and maintenance in buildings, system-equipment usage in buildings and lifecycle cost management. However, the resulting BIM files can be large and require significant computational resources. Therefore, BIM should be supported with NoSQL databases and BDA to eliminate inefficiencies in FM [48].

### 2.2. Building Energy Performance Simulations

Shaikh et al. [62] stated that "rapid energy depletion, rising building service demands, improved comfort lifestyles" result in more energy consumption. Furthermore, buildings are responsible for 30% of the total $CO_2$ emission in the world. Energy consumption of the building is a combination of "climate, building envelope, building energy and services systems, indoor design criteria, building operation, and maintenance, and occupant behavior" [63].

Building Energy Performance Simulations (BEPS) can be used in fault detection, optimization of building system operation, and prediction of building energy consumption. BEPS has the opportunity to observe energy losses and gains of the buildings. Energy gains can be lighting, solar radiation and heating radiation of equipment. Losses can be summarized as transmitting of heated or cooled air temperature between the indoor and outdoor environment [64]. It also enables to create and test different scenarios [65]. In other words, BEPS can be used to identify energy efficiency strategies [66]. In Table 2, some literature review about BEPS was summarized.

**Table 2.** Literature review for Building Energy Performance Simulations (BEPS)-FM studies.

| The Usage Area of BEPS | The Aim of the Studies | References |
| --- | --- | --- |
| Energy Efficiency Strategies | Development of energy efficiency strategies such as window opening according to the difference between outside and inside temperature, lighting (depending on occupancy, ambient light, timing schedule), HVAC schedules, thermal insulation and shadings, maximizing economy while satisfying power demand, optimizing components sizing, maximizing self-consumption, balancing between natural ventilation and air conditioning, human-in-the-loop optimization, comfort-driven optimization and occupancy-based optimization. | [5,26,66] |
| Fault Detection | Finding the problem and perform diagnostics according to the comparison of actual and predicted (from BEPS) energy consumption | [61,67,68] |
| Optimization of Building System Operation | Integration of BEPS and FM tools for optimization of building systems | [64,69] |
| Prediction of Building Energy Consumption | Usage of BEPS in energy management by integrating BEPS, actual energy consumption and genetic algorithm | [70] |

In the literature, the authors have performed lots of studies on the difference between actual energy consumption and predicted energy consumption. These differences can be attributed to various assumptions, misses and errors. Furthermore, De Boeck [71] stated that BEPS tools do not reflect real consumption values. Wilde (2014) explained the difference between actual and predicted as a function of time and outdoor environment. Furthermore, the author attributed performance gap problems to interoperability problems between design, construction and operation and maintenance stages. Burman et al. [72] indicated that actual and predicted energy consumption is different due to inaccuracies and uncertainties associated with model inputs, inadequacies of modeling methods and tools and building management and operational inefficiencies. Stundon et al. [73] performed a study that investigates the difference between actual and predicted energy consumption. The authors used 12 months of data to make a comparison. Furthermore, the authors said that "the BIM energy assessment tools are considered accurate, only if they meet the percentage difference criteria of within ±15%".

As a consequence, BEPS results can be used in building energy management and FM scenario testing. Furthermore, the existing studies showed that it also helps to identify maintenance requirements in the FM. This will be helpful to reveal wastes in energy management and increase client/end-users' satisfaction. Additionally, the usage of BEPS can provide a standardization process for FM energy management.

However, the study heavily emphasized that there is a measurement gap between actual and simulated results. To eliminate this issue, computational fluid dynamics (CFD) can be applied with BEPS. CFD is used to simulate flood flow among or around complex objects in the construction industry. The collocation of BEPS and CFD helps to obtain energy-efficient design and higher thermal comfort. In other words, the users cannot perform advanced analysis in BEPS due to convective heat transfer coefficients (CHTC) in BEPS [74]. For instance, Motazeri and Blocken [75] stated that CHTC was affected by building geometry, wind speed, wind direction, etc. because BEPS is using default values for CHTC in the analysis. Therefore, results deviate from accurate results. Such that results differ by 30% in cooling energy consumption at the low-rise buildings. At the high-rise buildings, this ratio increases by up to 42%.

*2.3. Big Data Analytics (BDA)*

Web-based application and sensor applications are becoming more ordinary in BIM applications. However, this requires more data storage and analysis. In this concept, BDA present an opportunity to handle data that come together with sensor and web-based applications [76]. BDA also provides an opportunity for interactive operations. This interactivity helps to collect information about customer/client/

end-user/inhabitant demands [77]. In other words, wastes, variations and non-value-added activities could be more apparent with the usage of BDA. Empirical studies, which are about facilities' use patterns, maintenance cost patterns and preventive maintenance planning, environmental degradation analysis, user behavior monitoring, finance, accounting and energy efficiency, proved that data mining approaches help to discover knowledge patterns [22,77,78]. Therefore, the authors stated that BDA would be a solution to maintenance costs, better service quality, accurate forecasting, risk mitigation, optimization and performance evaluation in the AEC industry. Furthermore, the performed workshop in the study proved that the potential integration area of BDA is the facility and operation management area in the AEC industry. The participants thought that the decision-making process could be improved with BDA integration in the FM phase. Furthermore, the most probable areas for the implementation of the BDAin FM are energy and maintenance management areas [22].

In the literature, the applicability of BDA in FM processes is investigated under energy studies, BIM-BDA integrated studies and maintenance studies. They were summarized in Table 3.

**Table 3.** Literature review for BDA-FM studies.

| Area of the Study | The Aim of the Studies | References |
|---|---|---|
| Energy | Development of energy management system by integrating BDA, GIS data, weather data, smart meter, IoT devices to identify energy usage, potential savings, implement different scenarios, energy cost estimation and increase energy awareness | [79,80] |
| | Usage of BDA in which smart meter data is processed to perform consumption analysis, the discovery of energy consumption patterns, customer segmentation and anomaly detection (by comparing historical data and neighborhood) | [81] |
| | Development of Big Data integrated cloud technology to optimize building energy consumption | [82] |
| | Investigation of the real-time flexibility of the electrical devices in the buildings | [83] |
| | Analysis of smart meter and sensor data to monitor building energy consumption, consumption pattern discovery, segmentation, forecasting, online anomaly detection, feedback service (such as alarms for emergency conditions), benchmarking energy consumption with neighborhoods, remote control and optimal schedules for electricity usage of home appliances and bill tracking | [81,84–86] |
| | Controlling of HVAC systems by using IoT data to enable energy efficiency in the buildings | [87] |
| | Integration of BMS/BAS and BDA to enable energy savings and to detect an abnormal condition | [88,89] |
| | Development of an intelligent data mining model to reveal energy consumption patterns | [90] |
| BDA Integrated BIM | Development of cloud technology to query BIM and dynamic data which comes from sensors with the integration of BDA | [91] |
| | Development of a framework for the integration of BIM and BDA to monitor energy consumption | [92,93] |
| | Integration of BIM and BDA to monitor energy consumption in BIM | [94] |
| | Integration of BIM and BDA to take a measure for the safety of occupants | [95] |
| | Integration of BIM and BDA to identify facility performance | [96] |
| Maintenance Management | Usage of BDA in predictive maintenance analysis for railway facilities | [97] |

As a consequence, the existing studies showed that the wastes related to maintenance, FM queries, energy optimization, energy consumption, prediction of future energy demand [98], detection of anomalies in buildings [89], energy-saving decisions [82], the discovery of energy consumption behaviors of users [99] and HVAC system optimization are a working area for BDA. However, the proposed systems do not offer comprehensive data analytics opportunities on FM data to reveal all wastes during the FM stage. A substantial part of the existing studies focused on the usage of real-time data. Additionally, some studies focused on limited parameters (such as ignoring building geometry or materials, building occupancy, limited weather parameters, etc.) in energy consumption forecasting. Furthermore, the developed studies do not consider the requirements of clients or end-users, which is vital in terms of LM practices. Additionally, the studies focus on one FM area for queries of information or analysis. Therefore, the developed solutions not only remain restricted in theory, but also induce inefficiency, and wastes, since they do not meet the FM requirements of clients. Additionally, other findings from the literature review showed that the combined use of BIM and BDA is extremely limited in published literature.

## 3. Lean Management Practices in Facility Management

Lean thinking aims to perform activities or services with fewer resources, fewer tools, less time, less physical space, high customer satisfaction, minimum non-value-added action and minimum waste [15]. In the FM, unnecessary inspection and repairs, breakdown, increase in downtime duration, rework, safety issues, high maintenance costs, efficiency and performance problems, rapid wear of components, excessive resource utilization and storage, timely decision making, transportation of materials, the unnecessary motion of staffs, variation in processes, data searching and customer dissatisfaction can be seen as application areas for LMP [4,9,12,100,101].

Aldairi et al. [100] proposed a knowledge-based management system that includes Lean Six Sigma for maintenance activities. Gao et al. [12] investigated the synergies between FM and LMP. Terreno et al. [4] investigated the applicability of the lean concept in BIM-FM to reduce wastes in information management. However, the study did not consider inefficiency and wastes, which can emerge depending on the lack of analysis of available information within BIM. McArthur and Bortoluzzi [102] investigated the lean and agile approach in FM-BIM implementation. Mostafa et al. [101] proposed a lean maintenance structure that is designed based on five lean principles; specifying the value, identifying the value stream, flow the value, pulling the value and pursue perfection. Shou et al. [9] proposed a lean management framework for maintenance acitivities. To verify the proposed framework, the authors used 4D BIM from a real-life environment. Sharma et al. [103] used LMP in healthcare service management to detect optimum resource allocation. Shou et al. [104] investigated the applicability of BIM and LMP in the maintenance process.

Although FM processes were elaborated in terms of maintenance and BIM utilization with LMP in the literature, there is no study or framework that covers all FM areas and helps to elaborate all wastes in FM by identifying required analysis and information types. Therefore, the above issues and operational and maintenance costs due to inefficient FM practices and data management comprehensively need to be handled.

As a result of the literature review, the processes of lean management philosophy were identified (Table 4).

**Table 4.** The processes of lean management philosophy.

| Stages | Sub-Process | Definitions | [105] | [12] | [4] | [100] | [101] | [9] | [40] |
|---|---|---|---|---|---|---|---|---|---|
| Preparation | P1. Base management decisions on a long-term philosophy, even at the expense of short-term goals | Harmony between short-term goals and the long-term philosophy | x | x | | x | | | |
| | P2. Create a continuous process flow to bring problems to the surface | Creation of continuous process to understand why change is necessary<br>• Information flow issues in the process<br>• The implementation of activity or process which is more than optimum<br>• Procurement duration for materials and equipment<br>• Waste of time and labor force due to information requirements for activities and processes<br>• Non-standardized processes<br>• Excessive inventory for necessary materials, equipment, and tools<br>• Rework activities due to pre-defined achievements goals<br>• Double handling<br>• Process bottlenecks<br>• Unnecessary and disorganized personnel movements<br>• Idle time for equipment<br>• Idle time for personnel | x | x | x | x | x | x | x |
| | P3. Establishing objectives | Selection of objectives after identifying issues in the process | x | | | | | x | x |
| | P4. Use "pull" systems to avoid overproduction | • Eliminate workload<br>• Eliminate overproduction | | x | x | x | x | x | |
| | P5. Improve the organizational structure | Improvement of organizational structure to eliminate<br>• Wastes in management<br>• Non-value-added activity and processes in management | x | | | | | | |
| | P6. Develop exceptional people and teams who follow your company's philosophy (including team training) | Hiring workers and co-workers who follow the lean principle | x | x | | | | | |
| | P7. Build a culture of stopping to fix problems, to get quality right the first time | Creating a culture based on benchmarking and comparing with hard data | | x | | | | | |
| | P8. Grow leaders who thoroughly understand the work, live the philosophy and teach it to others | The focus in FM is not just on the leaders, but on all employees within the FM team | | x | | | | | |
| | P9. Find a change agent | Finding a change agent | x | | | | | | |
| | P10. Integration of stakeholders (suppliers and customers) to processes and respect stakeholders by challenging them and helping them improve | Considering the expectations and objectives of stakeholders to achieve success | x | x | | | | | x |
| | P11. Select an appropriate production control approach | Selecting an appropriate production control approach | | | | | | | x |

**Table 4.** *Cont.*

| Stages | Sub-Process | Definitions | [105] | [12] | [4] | [100] | [101] | [9] | [40] |
|---|---|---|---|---|---|---|---|---|---|
| Design | D1. Use visual management | The usage of visual management tools to visualize data and its analysis | | x | | | | | x |
| | D2. Go and see for yourself to thoroughly understand the situation | Inspection of issues on site | | x | | | x | | x |
| | D2. Mapping the flow lines | Identification of cause-effect or input-output relationships of processes or equipment' working etc. | x | | | | x | x | |
| | D3. Use only reliable, thoroughly tested technology that serves your people and process | Using hard data comes from FM systems | | x | | | | x | |
| | D3. Analyze the business looking for improvement opportunities | Identification of improvement opportunities | x | | | | | x | x |
| | D4. Plan the implementation of improvements | Creation alternative scenarios for the elimination of wastes<br>• Balancing the workload of workers<br>• Balancing the workload of equipment in the facility<br>• Standardization of tasks<br>• Standardization processes<br>• Reduce variability,<br>• Reduce cycle times | x | x | | x | | x | x |
| | D5. Make decisions slowly by consensus, thoroughly considering all options; implement decisions rapidly | Considering the idea of all participants to increase the applicability of the selected plan and increase their understanding out their tasks and responsibilities | x | x | | | | x | x |
| | D6. Identify performance indicators | Creating success criteria that show the success of elimination of wastes or increase in productivity etc. | x | | | | | | |
| | D7. Create a feedback mechanism | Creating a feedback mechanism to improve FM decisions | x | | | | | | |
| Implementation | I1. Start with a pilot project | Starting with a pilot project | x | | | | | | |
| | I2. Evaluate the sustainability of the changes | Evaluating the sustainability of the changes | x | | | | | | |
| | I3. Changes in materials, systems and philosophies | Observing changes in materials, systems and philosophies | x | | | | | | |
| | I4. Raise awareness of the benefits of receiving changes | Raising awareness of the benefits of receiving changes | x | | | | | | |
| | I5. Pursue perfection (Become a learning organization through relentless reflection and continuous improvement) | The purpose of continuous improvement is to add value to the organization | x | x | x | | x | x | x |

## 4. Materials and Methods

The Design Science Research (DSR) methodology was followed to propose an architecture that requires iterative processes to eliminate process and resource wastes in FM. The main usage aim of this method is to find a better solution for the facility data management and data analysis in the facility [106]. The DSR was founded earlier than in 1966. The origin of the idea of DSR is that every design has its own creative processes. So, the main target of this method is to reveal both processes of design and the method in which artifacts are created. The outputs of this research strategy are constructs, algorithms, frameworks, models, methods and instantiations [107]. Furthermore, the iterative process, which is used in the strategy, is known as the most robust feature of the DSR methodology, since the iterative process helps to reveal lean methods and models. So, it provides an opportunity to create theory [106]. Gregor and Hevner [108] stated that the DSR helps one to find a more original and innovative solution for the problems. The DSR is commonly used in the investigation of information systems research. Since the DSR is preferred in decision support systems, modeling tools, management strategies, etc., the method helps to legitimate developed information systems.

The DSR methodology, which is used in this study, is given in Figure 2. The DSR methodology is applied under three categories: environment, design science research and knowledge base. In the environment, the business needs or issues are identified in the application domain (people, organizational systems, and technical systems) by considering the existing business process, corporate strategies, and culture. In the design science research, solutions/artifacts for business needs are built and evaluated by considering the existing body of knowledge. The developed artifacts must be undiscovered truth. Knowledge base helps to create new knowledge by getting knowledge from the existing body of knowledge [109].

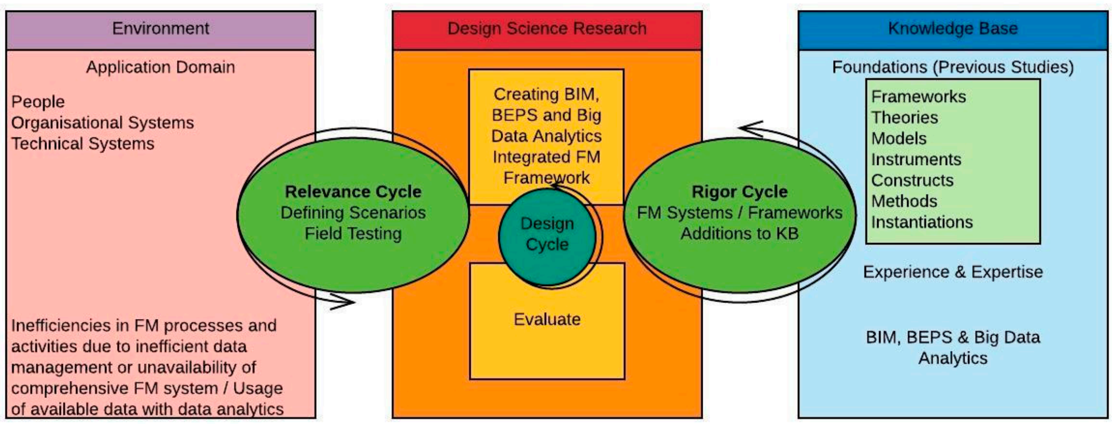


**Figure 2.** Design Science Research (DSR) oriented research methodology of the study.

DSR methodology also uses cycles to produce artifacts. They are:

- Relevance cycle: In the relevance cycle, the application domain is identified. Business needs, possible artifacts, and acceptability requirements for artifact are determined [107];
- Rigor cycle: The research foundations are defined. The research foundation also helps to identify whether the research includes new knowledge or not [107];
- Design cycle: The possible artifacts are built-in design cycle. Furthermore, the evaluation of artifacts is performed by considering acceptability requirements. If the requirements are not met, iterations are performed. The knowledge derived from assessments is used to improve existing foundations [107]. The evaluation of the created artifact provides feedback to improve the quality and design of the developed solution [109]. Different evaluation methods can be used to evaluate artifacts in DSR methodology. They are logical argument, expert evaluation, technical experiment, subject-based experiment, action research, prototype, case study and illustrative scenario [107].

The new knowledge creation procedure of this study is elaborated above three-cycle.

### 4.1. Relevance Cycle

Figure 1 shows the research vision. Based on research vision, an FM framework to be developed must comprise user requirements, the data storage requirements for identified data types, tools, activities, and data types for analysis. Two scenarios were developed to understand the nature of FM activities and data analysis requirements. The scenarios were created by conducting the interviews with a financial and administrative affairs manager with sixteen years of experience and a technician with nine years of experience who work in a healthcare facility (nearly 6500 $m^2$). They are:

- Scenario 1: Energy management during FM: This scenario enlightens energy management problems to see and understand the necessary procedure, necessary activities, data requirements and essential tools in FM.

The case healthcare facility does not have any energy management system in which energy consumption can be followed in real-time. The energy management process is followed by using billings. Therefore, manual efforts are heavily applied in the processes that are depicted in Figure 3. In the Figure, while arrows represent task relationships between facility management actors, rectangle objects represent tasks. According to the interview, the process starts with the request for investigation energy consumption by the facility manager. After that, the task is assigned to a technician. The technician collects energy consumption values from meters. Before any action is taken, the facility manager compares the collected values with historical energy consumption data. At this point, the facility manager decides whether the consumption is an acceptable level or not. If the consumption is at an acceptable level, the facility manager does not need to take any measures. However, if the consumption is not at an acceptable level, the facility manager would need to control and develop the solution manually. In the interview, the energy processes were requested to be evaluated in terms of lean principles by the interviewee. The findings showed that the harmony between the short-term and long-term goals was not considered in the healthcare facility. In other words, the management level did not set long term goals for energy consumption or preventing actions. Therefore, short term actions are planned and implemented without its impact on the long term. In the healthcare facility, the facility manager can only detect the energy consumption difference between months. If the big differences were detected between months and the previous year, all the facility was controlled with site visits, whether equipment or system, etc., which can cause more energy consumption. The interviewee stated that the frequency of the site visits depends on the difference between energy consumption amounts because the facility manager does not have any data, which helps to compare actual energy consumption. Furthermore, this situation causes a waste of time for the labor force. Moreover, it causes the implementation of site visits more than the optimum level. Additionally, the interviewee stated that there is no standardized procedure for energy management in the case healthcare facility. Therefore, idle time for personnel and equipment were not managed by the facility manager. Moreover, the facility manager could not perform data analysis to improve the facility. The interviewee also added the non-availability of the energy management system and the usage of data from these systems prohibit continuous improvement in FM.

- Scenario 2: Maintenance activities in buildings: This scenario helps to identify building maintenance problems to see and understand the necessary procedure, necessary activities, data requirements and essential tools.

Against the energy management process, a basic maintenance system (monitoring work orders, some information about equipment, etc.) was used in the maintenance process in the case hospital facility, which is shown in Figure 4. However, some lean issues were identified according to the interviewee's response. The interviewees stated that there are lots of equipment in the healthcare facilities, and every equipment requires different technical knowledge. For instance, anesthesia equipment broke down in the facility, and they cannot interfere due to a lack of knowledge about equipment. When the interviewees need this type of specific knowledge, this causes a waste of time and labor force due to information requirements for activities and processes. Rework activities were explained with an example. In the maintenance example, the facility manager prepared a bid for the reconstruction of the façade system since there is no openable window on the façade. After the tendering process, the contractor performed reconstruction activities. However, some broken windows and the opening issues were detected after site visits. Therefore, the facility manager requested rework activity from the contractor. Furthermore, the facility managers could only observe work orders. Therefore, idle time cannot be monitored by the facility manager. Additionally, the interviewee stated that the workload in summer is more than the workload in winter. Furthermore, fault type, fault duration, and their comparison against season and month could be followed. However, there is no prediction system for preventive maintenance in the healthcare facility, which has a negative impact on continuous improvement.

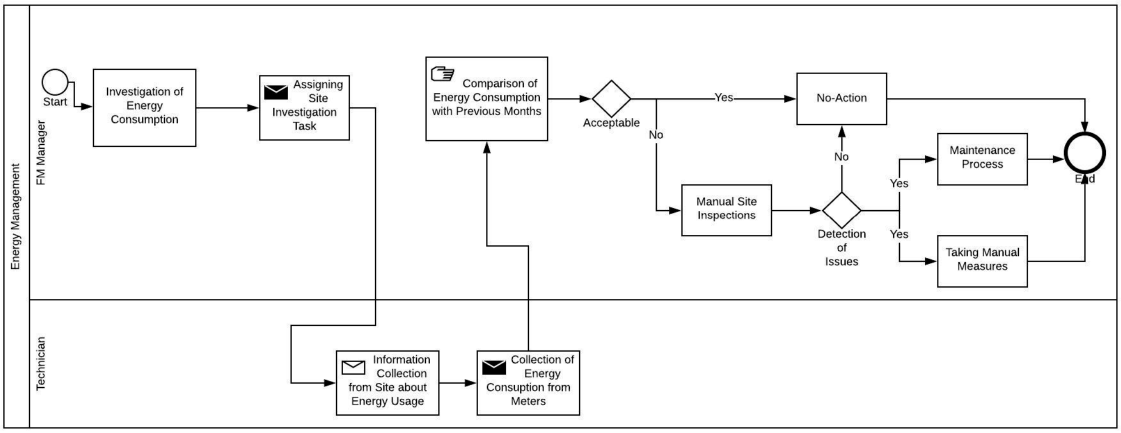


**Figure 3.** Scenario 1: Energy management during FM.

## 4.2. *Rigor Cycle*

This cycle helps to create research foundations by emphasizing research originality. Therefore, a comprehensive literature review is performed and given in Section 2. According to the literature review, it has been discovered that there is a limited study on BIM integrated BDA studies. Furthermore, the available studies consider limited and specific data types, such as energy, maintenance, etc., to perform data analysis. This prevents clarification of interrelations between data types. Additionally, IoT devices that are commonly used with FM systems have missing data and calibration issues. To eliminate these FM issues, there is a need for an FM framework that embraces the solutions for identified limitations in data analysis, FM queries, and FM data issues. This would help to:

- Usage of building data from the BIM model at the FM stage
- Improve information quality
- Usage of data analysis results in FM decision-making processes

Additionally, the Business Process Modeling Notation (BPMN) was used to reveal the processes of scenarios. In the literature, BPMN has been used in task management, resource allocation, data flow, and information systems. Business Process Management Notation (BPMN) is a technique in which the researcher or practitioners try to illustrate organizational processes because it is believed that efficiency and quality increase is hidden in organizational processes [110]. Moreover, BPMN techniques are also used in construction management literature. For instance, Lucas et al. [46] used the BPMN technique to show task distribution and to identify decision actors in facility management. Braun et al. [111] used BPMN to realize integrated hospital modeling for clinical processes.

### 4.3. Design Cycle

The steps of the framework were enlightened in the design cycle to create a general framework with the help of scenarios and literature review. The steps basically aimed to show which and when different kinds of information between different professionals need to be exchanged. This method is also called the Information Delivery Manual (IDM) [112]. Therefore, the steps were created by using the Cross-organizational Business Processes (CBP) modeling technique, which is used to define the organizational interactions. In CBP, process, actors, workflows, tools or software and information exchange need to be represented. Furthermore, so does the CBP-based BPMN [113,114]. The general process diagram is given in Figure 5.

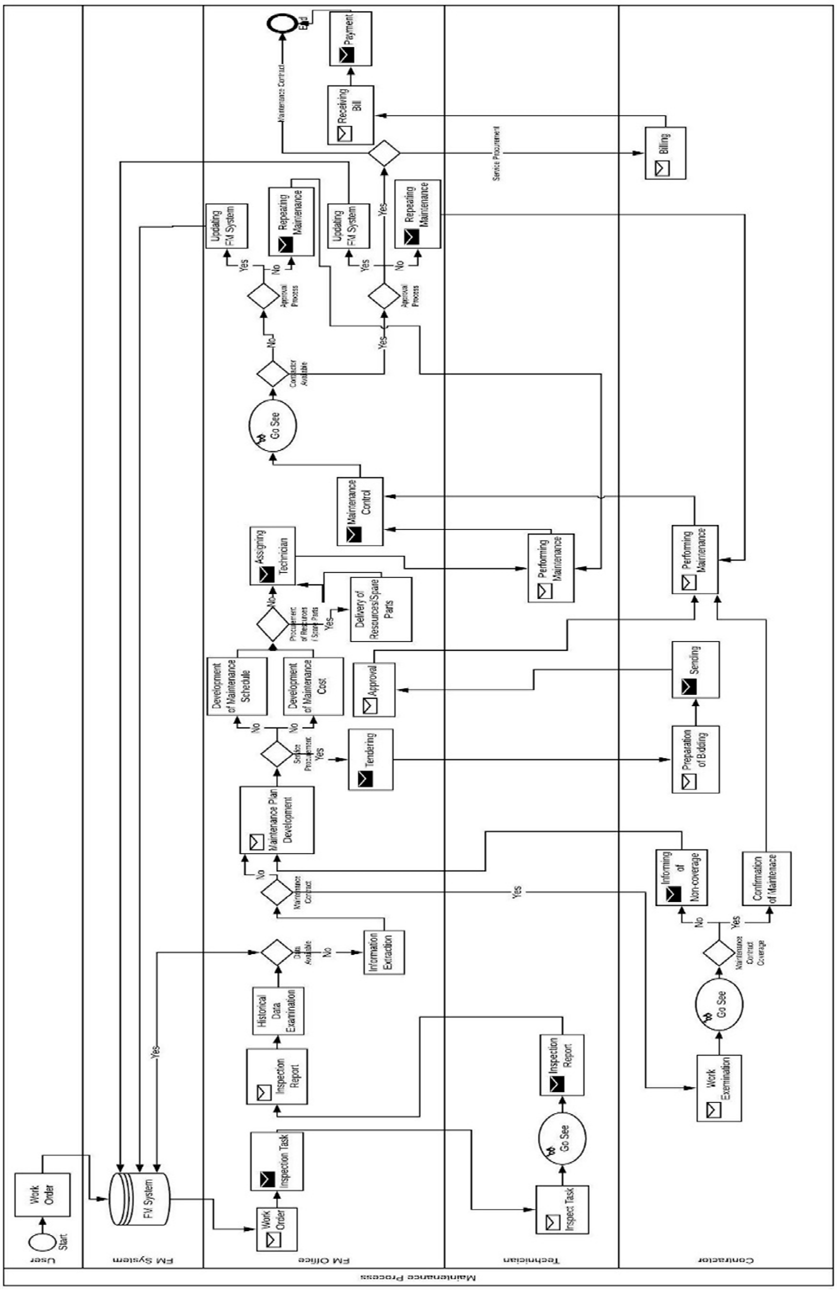

**Figure 4.** Scenario 1: Maintenance activities in buildings.

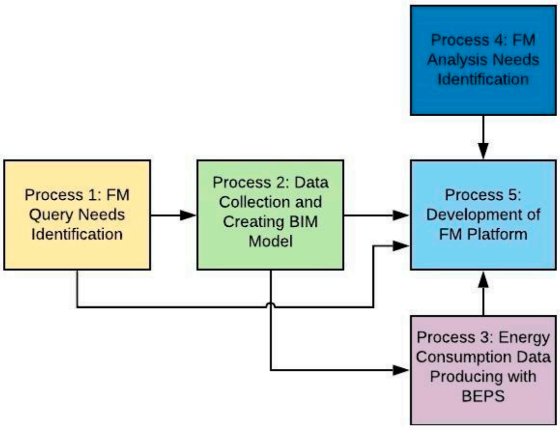


**Figure 5.** General Process Diagram.

In Process 1, the facility manager needs to identify required information types in FM, since facility managers do not need all information types, which are found in BIM or FM information systems. Additionally, unnecessary information types in FM systems induce data burden, which causes inefficient FM practices. Furthermore, identification and collection of necessary information types help information loss and lack of information for FM processes [43,44,115,116]. Therefore, in the first process, information types are identified as a result of the collaboration of facility manager and client/end-users. First of all, the identification of information types is ordered by conducting multi-criteria decision methods by the facility manager. This helps to eliminate unnecessary or less important information types. The information types are categorized under three categories: managerial information types, technical information types and financial information types. These information types were identified as specific to the healthcare facilities. However, the results of the important information types are another study topic since this paper aims to create a framework for the integration of BIM, BEPS and Big Data Analytics. After the categorization of information types, the identified information types need to be reviewed and approved by the clients/end-users. The output of this process is essential to determine which types of data will be collected in the BIM model and FM platform. For instance, if vendor information for equipment is essential, it must be attached within the BIM object. To define information types in BIM, Shared Parameters can be used to attach information types into the model. Furthermore, the outputs of Process 1 help to identify query algorithms in FM Software in which BDA codes are embedded (Figure 6). Furthermore, this process helps us to consider value-added activities in FM and eliminate inefficient wastes by realizing standardization in FM data management.

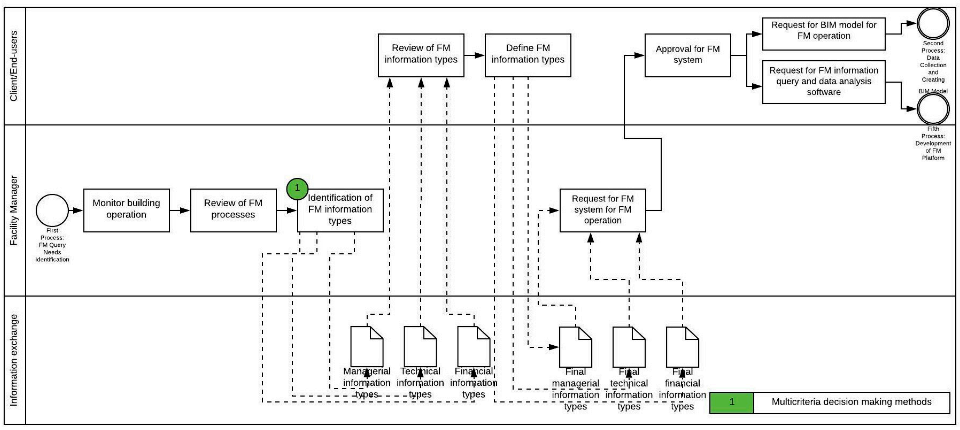


**Figure 6.** First Process of a Framework for Integration of BIM, BEPS, and Big Data Analytics in View of Lean Management Philosophy.

In the second process, the required information for the BIM model is collected from the building and building environment with the help of the facility manager. The information required to create a BIM model can be reviewed under three categories. They are FM data, investigation of building component data and site data. FM data involves necessary data, which are defined in the first process. Therefore, the first process has vital importance to embed necessary information into the BIM model. Investigation of building components is essential to perform energy analysis since building components and their characteristics such as reflectivity, thickness, thermal conductivity, etc. are required for energy analysis.

Furthermore, as-built models (architecture, structural, and mechanical, electrical and plumbing (MEP) plans) are essential to reflect the current condition in the building because a created BIM model at the design or construction stage cannot include updated and necessary objects for FM. The delivery of the as-built BIM model needs to be performed with the help of an architect, construction engineer and MEP engineers. The outputs of this process are also used in the creation of an energy model of the building. To enable interoperability, gbXML and IFC formats can be used [117,118]. However, some issues must be considered in the creation of the BIM model. For instance, BEPS does not necessitate columns and beams since two-dimensional analysis is performed in BEPS. Therefore, it does not require beams and columns. When beams and columns are modeled in BIM, building zones are not enclosed. Therefore, the architects also need to deliver a BIM model without FM information and other objects which cause a problem in energy analysis programs. Moreover, the information in the BIM model needs to be transferred into the NoSQL Database to use them in analysis and queries (Process 5).

Additionally, when BIM is used in maintenance management, lots of data must be attached to the objects. However, BIM gives limited data size fastening opportunity. Furthermore, overwriting causes loss of historical data. Therefore, data storing with an external database is essential (Figure 7).

As stated in the literature review, BEPS can be used in energy management. To use them in FM, a real condition in the facility needs to be reflected. A weather data file (from weather stations) plays a vital role in finding building energy consumption after other required information is entered in the simulation model. When the building is simulated at the design stage, energy analysis is performed by using a specific data file (such as 2002 weather data file in DesignBuilder) since this data file reflects more stabilized weather data sets. If the data file is changed with current weather data, which is obtained from weather data stations, energy consumption information, which is more approximate to actual conditions, can be obtained. In the literature, energy consumption estimation was performed by changing limited weather data and other building-related parameters. Some of them can be seen in Amasyali and El-Gohary [119]'s study. Besides weather data files, building equipment, building operations, and building geometric and thermal information needs to be added into the simulation model. Therefore, before building energy consumption simulation is performed, operational data (including weather data, building equipment) and building geometry and component data (from BIM) need to be prepared by the facility manager. In the study, the usage of the integration of BEPS-CFD is offered to reduce the gap between actual and simulated energy consumption. The possible data transfer between BEPS and CFD can be seen in [117]. After BEPS results are retrieved from software, the validation of energy consumption data needs to be performed with the usage of monthly bills. To validate consumption values, Root Mean Square Error (RMSE), Mean Absolute Error (MAE), coefficient of variance ($R^2$), and coefficient of variance (CV) can be used. While MAE is the mean difference off-set between actual and predicted values, RMSE measures the standard deviation of residuals. RMSE and MAE define prediction errors. CV is helpful to compare the obtained results with other studies. Furthermore, $R^2$ measures the goodness of fit between actual and predicted values (should be between 0 and 1) [118]. After obtaining energy analysis results, client/end-users and facility manager need to identify performance criteria and FM requirements for energy management. After final key targets are defined by the facility manager, alternative actions need to be defined by the facility manager. These alternative actions can be determined by the client/end-user since alternatives include maintenance, changing operational behavior or further analysis with the support of Process 5.

Finally, the data is transferred into NoSQL databases to make more analyses and queries on FM software (Figure 8).

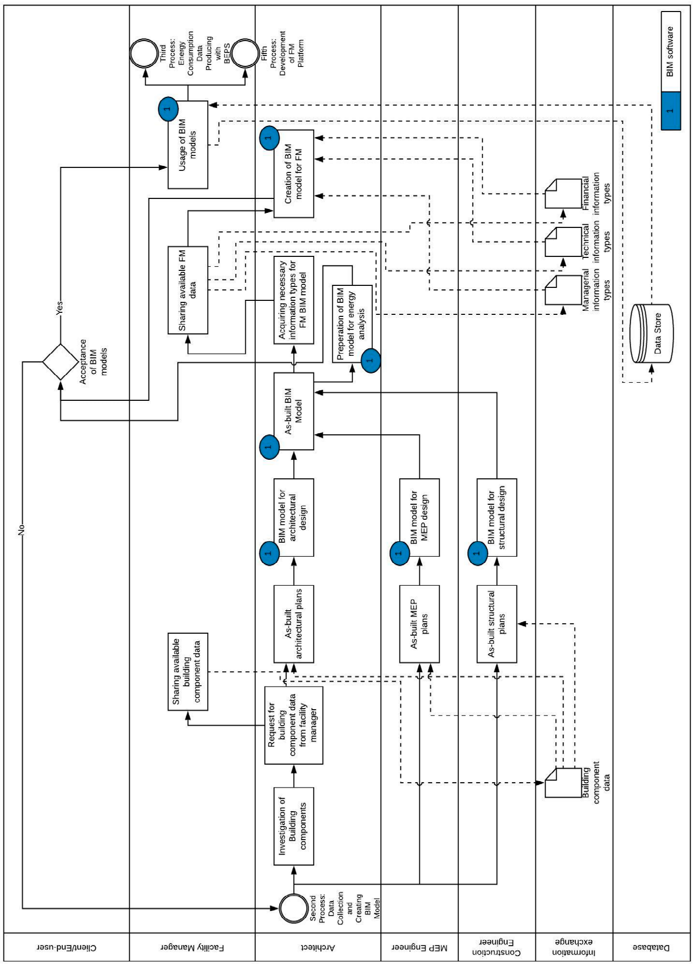


**Figure 7.** Second Process of a Framework for Integration of BIM, BEPS, and BDA in View of Lean Management Philosophy.

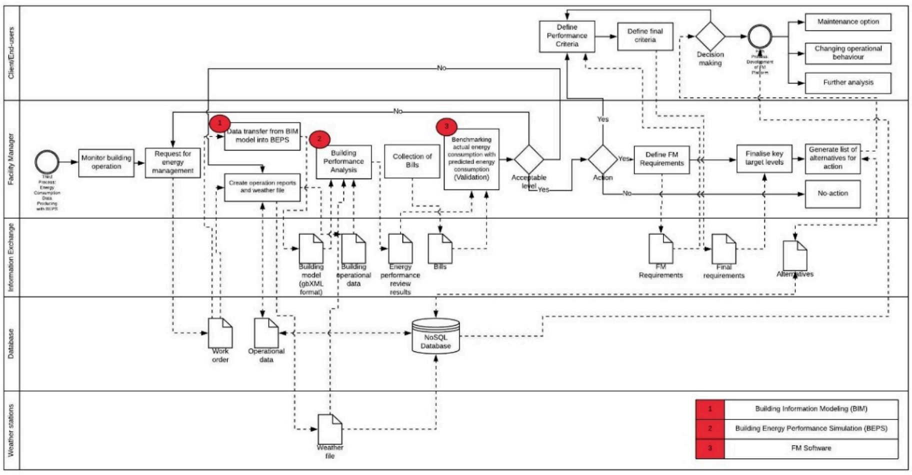


**Figure 8.** Third Process of a Framework for Integration of BIM, BEPS and Big Data Analytics in View of Lean Management Philosophy.

In the fourth process, FM business intelligence and analytic areas need to be identified to use available data more efficiently and effectively in FM. This also helps to obtain lean processes in FM. Available data in FM systems could be used to improve building performance in different areas. These areas can be grouped as energy consumption, user behavior, emergency and safety management, maintenance and repairs, usage of system-equipment, and lifecycle cost management. Every area has its own sub-analysis items. To identify these sub-analysis items, the literature review was performed. For example, "identification of energy consumption against time, user profile, spaces, weather, window openings, and geographical location, energy optimization" etc. in energy consumption category were identified. These sub-items need to be determined to embed them in developed FM software to eliminate the external data analysis package. This will facilitate data-driven decisions in FM.

Additionally, the lack of data analysis tools in FM systems and BIM will be eliminated with the proposed framework. Therefore, first of all, the analysis types need to be ordered with the help of Multi-Criteria Decision-Making Methods by the facility manager. After ordered analysis types are evaluated by client/end-users, the identified analysis needs to be embedded into FM software (in Process 5) (Figure 9). However, the results of the identification of FM business intelligence and analytic areas is another study topic since this paper aims to create a framework for the integration of BIM, BEPS and Big Data Analytics.

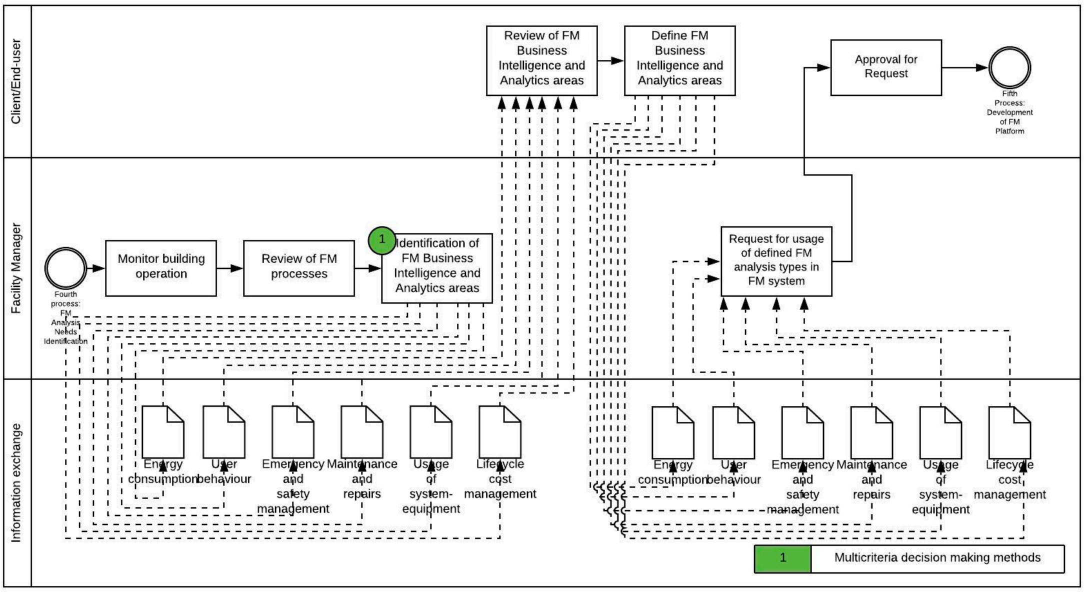


**Figure 9.** Fourth Process of a Framework for Integration of BIM, BEPS and Big Data Analytics in View of Lean Management Philosophy.

In the fifth process, the outputs which come from the identification of FM information types and FM business intelligence and analytics areas are coded in FM software by software engineers. In the study, NoSQL Databases were chosen. Relational database management systems (RDBMS) were used for data management for energy management and facility management in the literature. However, these systems suffered from seeking processes, which means read and write processes take more time. Furthermore, these systems are limited and inefficient in terms of architectural change. Another drawback of the RDBMS is that RDBMS only focused on structured data such as XML documents [119]. When the NoSQL database is built, the FM information procured by the facility manager is stored in the developed database to use them as queries, analyses, and predictions.

In the framework, the use of the MapReduce algorithm was chosen, since the advantage of MapReduce is that the queries on datasets can be performed within the tolerable time. MapReduce is a batch processing system. It is used to process data. MapReduce is worked on parallel systems which necessitate machine slaveries. MapReduce consists of the Map phase and Reduce phase, and each phase uses input and output key-value pairs. The map function is like a data preparation phase. After the data preparation phase, the reduce function takes part to find query answers. Furthermore, the map function helps to eliminate bad and unused records (missing, suspicious or erroneous) [119]. In the developed framework, the MapReduce function will be coded in FM software with the usage of Python language by the software engineer. Analysis and estimation codes that are obtained as a result of Process 4 (identification of FM business intelligence and analytics areas) are also coded with the help of data mining, text mining and visual analytic techniques, which are used together with Big Data Analytics by the software engineer. As a result of all processes, the results of data analysis and the query will be shown on FM software (Figure 10).

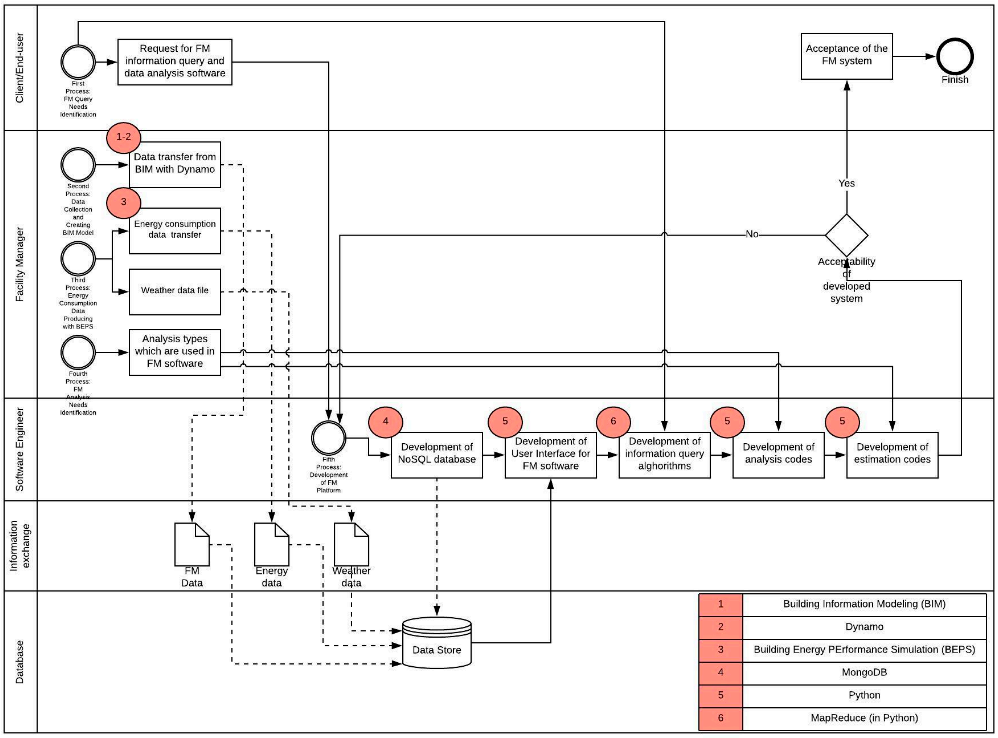


**Figure 10.** Fifth Process of a Framework for Integration of BIM, BEPS and Big Data Analytics in View of Lean Management Philosophy.

The expert evaluation was chosen to evaluate the developed framework [107]. The evaluation of the proposed FM framework will be discussed in Section 4.

## 5. Discussion

The developed scenarios were used to identify facility management issues such as data management, data analysis, FM tools and data transfer. According to the findings from scenarios, a framework that integrates BIM, BEPS and Big Data Analytics was offered. The proposed framework is given in Figure 11. The framework consists of five main processes. In Figure 11, arrows represent information flow between processes and tools. The last step is to create an FM software user interface, which makes a connection between requests for queries and analysis by using data from the NoSQL Database and Big Data Analytics. With the main lines, Process 1 (Identification of FM Information Types) enables to input requirements for Process 2 (Data Collection) and Process 5 (Development of Queries). Process 2 (Data Collection) provides data input from the BIM model to NoSQL Database and Process 2 and 3 (data transfer from Revit to BEPS software). Process 3 includes the creation of building energy data obtained from BEPS tools. Process 3 creates input for NoSQL Database to use them in analysis, which is in Process 5. Process 4 (Identification of FM Business Intelligence and Analytics

Areas) enables identification of data analysis requirements for Process 5 (Development of Analysis Codes and estimation codes).

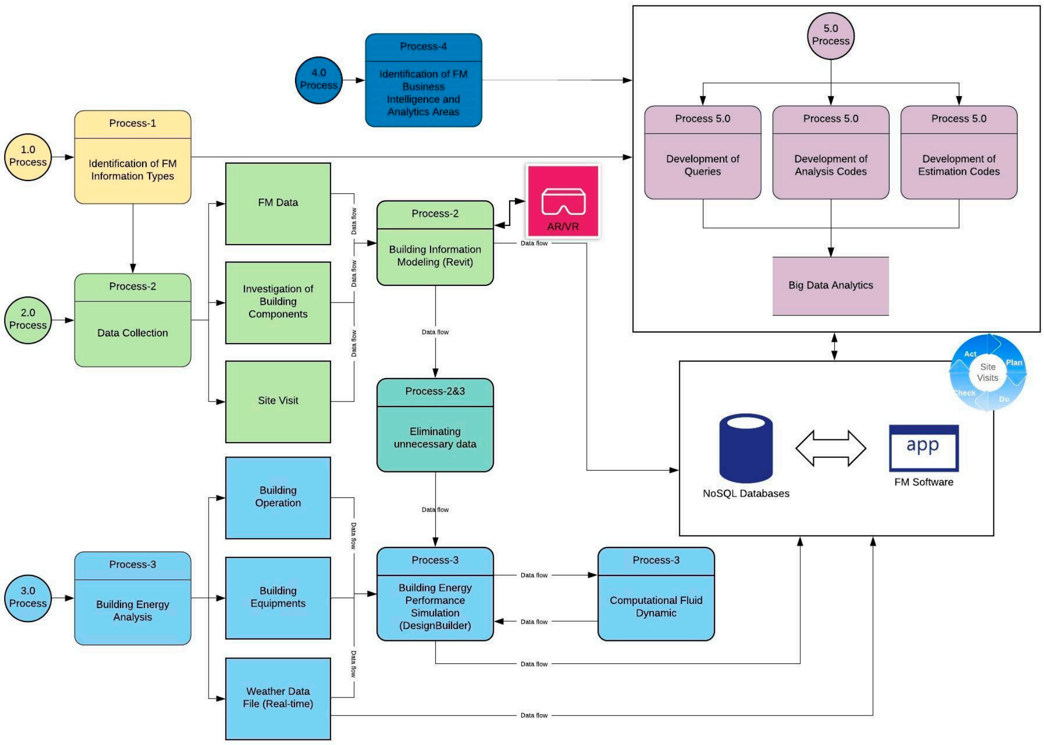


**Figure 11.** A Framework for Integration of BIM, BEPS and Big Data Analytics in View of Lean Management Philosophy.

To evaluate the developed framework (Figure 11), three interviews (a half-day interview) with four experts were conducted. The first and second interviews were performed with interviewees who are from multinational companies. The third interview was conducted with two interviewees who have experience in Public-Private Partnership healthcare facilities. The descriptive information about experts was given in Table 5. Before interviews were conducted, the brief about the framework and concepts such as BIM, BEPS and BDA was given to interviewees. Firstly, it was requested from interviewees to evaluate the applicability and feasibility of the developed framework in facility management (for the first research question). Secondly, the interviewees were requested to evaluate the framework's advantages and disadvantages with open-ended questions in view of lean management philosophy (for the second and third research questions). These questions were created as a result of a literature review about lean management philosophy (Table 4).

**Table 5.** The profile of experts who participate in the evaluation stage.

| Interviewee | Profession | Experience | Expertise Area |
|---|---|---|---|
| I1 | Civil Engineer | 7 years | Lean Management and BIM |
| I2 | Civil Engineer | 4 years | BIM, Digital Twin, Facility Management |
| I3 | Electrical and Electronic Engineer | 13 years | Public-Private Partnership Healthcare Facility Management (5 Healthcare facilities, approximately total 7000 beds) |
| I4 | Civil Engineer | 8 years | Public-Private Partnership Healthcare Facility Management (5 Healthcare facilities, approximately total 7000 beds) |

- Opinions about applicability and feasibility of the proposed framework: According to the interviewees, the feasibility of the proposed framework was found feasible. Data collection process and accuracy of the framework were evaluated as the most important part of the proposed framework by the first and third interviewees. Additionally, it was recommended that the applicability of the proposed framework should be customer-focused and take into consideration of continuous improvement. According to the second interviewee, the proposed model is near to industrial applications. The second interviewee stated that the BIM model could be used as a support system in FM, and asset management can be performed with the consideration of all FM information types and BIM that are given in the proposed framework. Furthermore, the proposed framework was found very comprehensive in terms of FM by all interviewees.

- Lean view about the proposed framework: According to expert view, the answers to open-ended questions were given in Table 6.

**Table 6.** Expert Views.

| Question | Interviewee | Opinion |
|---|---|---|
| Standardization | I1 | One of the most significant contributions of the proposed framework was found helping standardization in FM processes since the proposed framework helps to identify and manage the required information. Additionally, the analysis of is information facilitates the planning and decision-making process for appropriate activities. |
| | I2 | The interviewee stated that the proposed framework presents a controlling mechanism for FM. Therefore, the interviewee believed that the framework contributes to standardization in FM activities and processes. |
| | I3, I4 | The proposed model will contribute to standardization in FM processes. However, the interviewees stated that changes in the FM realize within years. Moreover, FM and building operation data will play an important role in this change. Therefore, the planning of the change needs to be considered in the model. Within this context, it is believed that the extensible structure of the NoSQL database will be helpful. |
| Harmony between short-term goals and the long-term philosophy | I1 | In lean management, acquirements from short term decisions were defined as necessary by the interviewee since it helps to consolidate commitment to lean management in FM. With the help of the database, the results of the activities or plans will be saved. In other words, the appearance of the decisions and outcomes in FM will be more transparent to improve both actions and processes for the next applications. Furthermore, the interviewee stated that continuous improvement (pursue perfection) with the Plan-Do-Act-Check cycle would help to find out the impact of short-time decisions on long term decisions. Therefore, the harmonization of the short time decisions and long time decisions can be observed and provided with the proposed FM framework. |
| | I2 | The interviewee stated that the model has a positive impact. |
| | I3, I4 | Interviewees approached the harmonization of the short-term decisions with long term decisions like consideration of the lifecycle of the project since they have FM issues due to the non-consideration of FM requirements in the design stages. Therefore, they suggested that the usage of the proposed framework needs to start at the beginning of the project to determine data collection points properly. |
| Process bottlenecks | I1 | The interviewee expressed that the Plan-Do-Act-Check cycle will reveal process bottlenecks, and it will be helpful to remove them in FM since the learning from experience shows bottlenecks in the processes. |
| | I2 | The second interviewee stated that the proposed FM framework would be beneficial to remove process bottlenecks since all information can be observed from a common data management system (the proposed FM system). |
| | I3, I4 | According to the third interview, the proposed framework is also helpful to eliminate process bottlenecks. However, the interviewees stated that bottlenecks which are originated from external factors such as purchasing or service procurements from suppliers, could be integrated on FM software. Therefore, the interaction between facility managers and other stakeholders can be conducted on FM software. This part is out of the scope of this study. However, after the development of the framework is performed, it will be applied. |

**Table 6.** *Cont.*

| Question | Interviewee | Opinion |
| --- | --- | --- |
| Continuous improvement | I1 | One of the main contributions of the framework was found as continuous learning due to the integration of past data into new FM processes and activities. |
| | I2 | The interviewee stated that constant improvement could be provided with the proposed framework since the monitoring can be performed. Therefore, the interviewee believed that facility managers could make a better decision by the usage of monitoring results. |
| | I3, I4 | According to the third interview, the usage of predictions and results in FM will be possible with the increase in data and their analysis in Process 5. The interviewees stated that the usage of analysis and data would also help to discover more effective and efficient FM activities. |
| The implementation of activity or process which is more than optimum | I1 | To implement optimum activity and process in healthcare facilities, the facility managers need data. When all wastes are removed in the processes and activities, the optimum implementation for activities and processes is achieved. According to the interviewee, the proposed system helps to eliminate unnecessary activities and waste with the help of cycles since the optimization of activities and processes can be more explicit in every cycle. |
| | I2 | The interviewee stated that the usage of the BIM model, the collection of FM information types, and their analysis would help to save necessary data in the FM platform. The interviewee believed that the availability of data would pave the way for seeing wastes. |
| | I3, I4 | According to the third interview, the interviewees stated that the collection of the necessary data from the beginning of the design stage is very important. The interviewees believed that after this information is collected, the optimum activity and processes in FM can be implemented. The authors believed that the first process would be helpful to determine the necessary information types which are collected during the design and construction stages. |
| Idle time for equipment | I1 | The interviewee stated that the equipment needs to be ready to give a service to patients in the healthcare facilities. Furthermore, when the patient is not available, the equipment should not be working at this time. If the idle time for equipment and patients (when necessary service from equipment waits) are available, they have identified wastes in view of lean principles. |
| | I2 | The second interviewee stated that within the proposed model, identified information types (equipment/system operation schedule in technical information types and spatial occupancy information and schedule in management information types) could be used to eliminate idle time for equipment (wastes) in the process. Therefore, optimization of equipment idle time can be performed. |
| | I3, I4 | Interviewees stated that the most and least needed equipment could be followed, and co-aging in equipment can be realized with the usage of the existing of these information types. The interviewees believed that this would also be helpful in reducing energy consumption and maintenance costs. |
| Excessive inventory for necessary materials, equipment, and tools | I1 | According to the interviewee, just-in-time, which is used lean philosophy, proposed not to store any equipment and materials in the lean management. Therefore, spare parts or other storages for materials are seen wastes in lean philosophy. The interviewee stated that procurement time needs to be shortened instead of storage. Within this context, the interviewee noted that fault detection and preventive maintenance, which are considered in Process 4, would be helpful to both impede waiting time for procurement and excessive storage. The interviewee added that procurement time needs to be entered in a maintenance plan (in Process-1), and the procurement time should be used to impede excessive storage because FM has a limited budget, and it can be saved to use them in a different area. |
| | I2 | The interviewee stated that the match between the availability of spare parts and work orders, which are collected in the first process, can be performed with the usage of the proposed framework. Thus, the critical spare parts for healthcare facilities can be stored in the facilities to impede stop in the operations. Furthermore, the interviewee stated that the proposed framework allows us to perform preventive maintenance. The interviewee believed that this helps to impede excessive storage of spare parts and materials. |
| | I3, I4 | According to the third interview, identification of the most needed equipment and materials can be revealed in Process 5. The interviewees believed that the materials and equipment which have long procurement time could be determined and stored with the help of a developed framework. |

**Table 6.** *Cont.*

| Question | Interviewee | Opinion |
| --- | --- | --- |
| Waste of time and labor force due to information requirements for activities and processes | I1 | The interviewee stated that the proposed model definitely helps to solve issues related to finding necessary information or information issues in FM. Furthermore, the interviewee expressed that the model helps to improve planning for the next activities or processes by using previous existing information with BDA. Additionally, the interviewee stated that even if lots of data is stored in the database and we do not know how the existing data will be used, it is another waste for FM. The first interviewee believed that a given framework would be a guide to transforming data into information for necessary FM activities. |
| | I2 | The interviewee confirmed that the proposed framework could provide all information specific to building within the tolerable time since BIM usage allows to store all information, which is found in the proposed framework. |
| | I3, I4 | The third and fourth interviewees stated that the developed framework would have a positive impact on both the material planning process and staff planning. Therefore, the interviewees believed that the proposed framework would be helpful to prevent loss of labor and time due to the finding of the necessary information. |
| Rework activities due to pre-defined achievements goals andDouble handling | I1 | The interviewee believed that plan-do-act-control and saving their results in the database would help to eliminate rework activities. Furthermore, the interviewee stated that standardization efforts help to reduce rework activities, double handling activities, and unnecessary or unorganized staff mobility since if the standardized activity or process gives different results, it means it is not standardized. The interviewee gave a maintenance plan (in managerial information types) example in which every activity is defined. Therefore, double handling can be removed in the maintenance issues. |
| | I2 | The interviewee stated that the proposed framework would help to perform more planned FM. Furthermore, the interviewee noted that the result of BIM usage is already to eliminate rework and double handling activities. |
| | I3, I4 | The third and fourth interviewees stated that data storage and their analysis would impede the repetition of work and give direction to more efficient activities and processes. Therefore, they believed that rework and double handling would be improved with the usage of the proposed framework. |
| Idle time for personnel | I1 | The interviewee stated that Kanban tables in which there is feature work, performed work, and in-progress work, is typically used to follow staffs' work hours in lean management philosophy. However, the competent personnel (in Process-1) and the development of the team, which is responsible for maintenance and repairs and optimization of maintenance overtime (in Process-4), can partially improve idle time for staff. Furthermore, the interviewees confirmed that work orders, which are found in the database, help to identify assignment history according to staff name. This will be helpful both to find out idle times for staff and to retrieve the expertise area of staff specific to maintenance. |
| | I2 | The interviewee warned that the healthcare facilities generally have maintenance contracts to perform maintenance activities in the facilities, and the idle time may not be managed by facility managers in the healthcare facilities. Therefore, identification of idle time for healthcare facilities cannot be controlled by the facility managers. Furthermore, maintenance contracts could lead to data loss. |
| | I3, I4 | Third and fourth interviewees, who perform maintenance management in healthcare facilities, stated that the cost of staff and spare parts and consumables are the costliest items in FM. The interviewees believed that the usage of analysis in FM software would significantly reduce staff requirements in the planned maintenance. Furthermore, the interviewees added that it has an impact on the optimization of idle times for staff by increasing their productivity. |

**Table 6.** *Cont.*

| Question | Interviewee | Opinion |
| --- | --- | --- |
| Improvement of organizational structure to eliminate wastes in management and non-value added activity and processes in management | I1 | The interviewee stated that the identification of wastes and non-value-added activity is not an easy task. Therefore, the interviewee suggested that site investigation needs to be inserted into the proposed framework since site investigation helps to identify the actual situation in the facility. Therefore, it was added within the Plan-Do-Act-Check cycle, and the framework was revised. |
| | I2 | The interviewee stated that the proposed framework presents monitoring opportunities for FM, and it is already a decision support system. Therefore, the interviewee confirmed that the framework would be helpful in eliminating wastes in the management process. |
| | I3, I4 | The third and fourth interviewees stated that business management, reporting, monitoring activities on site, etc., which are some of the management activities, will be reduced with the application of FM software. Therefore, the interviewees believed that the framework would enable time savings, plain and more easily manageable processes. |
| Inspection of issues on site (Go and See) | I1 | The interviewee stated that the site investigation is vital for a go and see principles which are found in lean principles. |
| | I2 | The second interviewee proposed integration of AR or VR technologies into the proposed FM framework since Augmented Reality (AR) or Virtual Reality (VR) can help to understand and discuss the issues, which are observed from work orders, and develop solutions on the site. Therefore, the proposed FM framework was revised, and AR or VR was integrated into the model. |
| | I3, I4 | In the third interview, the interviewees stated that site visits are the most time-consuming activity in the FM. Therefore, the interviewees emphasized that the optimum team size, routes, and site visit scope need to be identified. The interviewees stated that the proposed model has a partially positive impact on the implementation of "go and see principle" in FM since the planning of site visit routes with BIM and identification of site visit scope with FM framework can be possible. |
| Identification of improvement opportunities | I1 | The interviewee stated that the inclusion of site investigations could help to improve the understandability of the opportunity of the business process. |
| | I2 | The interviewee stated that the proposed FM framework could detect such as excessive energy consumption in the healthcare facilities. According to the experience of the interviewee, over-design can be realized in the design stage. Depending on the over-design, excessive energy consumption can be observed. The interviewee stated that the proposed FM framework is helpful in identifying opportunities such as energy consumption etc. |
| | I3, I4 | The third interview showed that the regular evaluation of FM decisions with patients or end-users in the facility would increase the identification of new opportunities for facilities. Therefore, the authors believed that the existence of measurement and prediction of user satisfaction (in Process 4) would be helpful to improve FM. |
| The usage of visual management tools to visualize data and its analysis | I1 | The interviewee stated that the visualization needs to comply with A3 Problem Solving. All results from the system need to be showed on A3 page size and only required data showed to facility managers or staff. Otherwise, for example, the information on more than A3 page size will lead to loss of information. |
| | I2 | The second interviewee stated that the proposed framework is convenient for data analysis and its visualization with the help of FM software. |
| | I3, I4 | Third and fourth interviewees stated that the visualization of analysis helps to increase the contribution of non-technical personnel in the FM process. Therefore, the interviewees believed that the developed framework with the data analysis and their representation on the FM software would be helpful. |
| Identification of cause-effect or input-output relationships of processes or equipment' working etc. | I1 | The interviewee gave an energy consumption example, which is found in the framework. According to the opinion of the first interviewee, the framework is helpful in detecting input-output and cause-effect relationships since the users can observe different results according to the number of people in the room. The contribution of the proposed framework in terms of identification of cause-effect and input-output relationship among processes, equipment, and systems were also found positive by the second interviewee. |
| | I2 | The interviewee stated that cause and effect could be observed with the integration of AR or VR technologies into the proposed framework. Therefore, the usage of these technologies will show the impact of one system on the other system. |
| | I3, I4 | The interviewees did not make any comments. |

**Table 6.** *Cont.*

| Question | Interviewee | Opinion |
|---|---|---|
| Reductions in variability, and cycle times | I1 | The interviewee attributed reductions in variation and cycle time to standardization. The interviewee stated that the proposed framework would also help the optimization of variety and cycle time due to Process 1 and Process 4. |
| | I2 | The interviewee stated that down-time of system or equipment could be eliminated with preventive or predictive maintenance, which helps to reduce the required time for cycle times of maintenance. |
| | I3, I4 | The third and fourth interviewees stated that the execution of analysis in Process 5 helps to reduce both variation and cycle time since data analysis will lead to an increase in productivity. |
| Creating success criteria that show the success of elimination of wastes or increase in productivity etc. | I1 | Besides, identification and measurement of Key Performance Indicators (KPIs) for FM (as a lean principle) was reported significant by the first interviewee since the facility manager needs to observe their success in FM. Thus, learning from past failures can be measured. |
| | I2 | The second interviewee stated that every process, which is given in the proposed FM framework, can be thought of as a KPI, and the proposed framework helps to measure them. |
| | I3, I4 | The third and fourth interviewees stated that the framework would be helpful to the identification and measurement of KPI for FM. According to the interviewees' example, work orders can be analyzed in terms of both workforce and time with the usage of the proposed framework. The interviewees believed that these KPIs would be helpful in comparing actual performed values with Service Legal Agreement (SLA) values. Therefore, the interviewees stated that the framework would provide feedback for the implementation of SLA. |
| Using hard data comes from FM systems | I1, I2, I3, I4 | Moreover, using hard data coming from FM software was found another essential feature of the proposed framework by the interviewees since the proposed framework has a database. Furthermore, the interviewees stated that if data is not recorded, the opportunity for more lean activities cannot be delivered. |
| Raising awareness of the benefits of receiving changes | I1, I2, I3, I4 | The proposed framework was found as deficient in terms of an increase in FM awareness due to the non-availability of lean training. However, the second interviewee stated that the framework helps to increase awareness of facility managers. |

## 6. Conclusions

As a result of the comprehensive literature review, the studies showed that there is no study in which all FM data was comprehensively handled and managed. Therefore, this study aimed to propose an FM framework for the healthcare facilities, which includes BIM, BEPS and BDA, by combining the FM framework with LMP.

The Design Science Research Methodology was followed in the study. Within this context, two FM scenarios from a healthcare case were evaluated in terms of lean management philosophy. By considering issues, which are observed in case study scenarios, and literature review, an FM framework that consists of five steps was created. After the steps of the FM framework were clarified, the main FM framework, which combines BIM, BEPS and BDA, was evaluated by expert evaluation method in terms of applicability and lean management philosophy. The result of the proposed FM framework showed that experts did not find any issues in the applicability of the proposed FM framework. However, the experts offered that the customer, site visits and integration of AR or VR technologies need to be considered in the application of the proposed framework. Therefore, the revisions of the proposed FM framework were performed.

The developed framework will guide healthcare FM people on how to implement a client/end-user-focused FM platform, more efficient data management and how the synergies between FM and LMP can be created. It is believed that the usage of the proposed framework will contribute to increase the efficiency of FM practices and eliminate FM wastes. The proposed framework can be applied to other building types. However, Processes 1 and 4 need to be identified according to the literature review and experts specific to building types. As a limitation, the proposed FM framework is theoretical. However, the study will be applied to a real case as a further study. On the other hand, the development of the proposed FM framework is limited to two FM scenarios. As a further study, the development of the FM platform will be performed according to the defined processes in the study.

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