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ND BIM-integrated knowledge-based building management: Inspecting post-construction energy efficiency

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ABSTRACT

Inspection of sustainable performance during post-construction has become increasingly essential. However, conventional operation and maintenance processes are limited with a high probability of inaccurate manual building inspections and the lack of real-time input of dynamic factors. In this regard, engagement of an Integrated Knowledge-based Building Management System using nD BIM applications (nD BIM-IKBMS) is anticipated to promote promising resolutions. The proposed system is expected to provide simulation-based supervisory control while automatically detecting and diagnosing operational faults. Following the literature-based conceptual model developed in our past research, this study aims to generate and verify the proposed framework theoretically, as the second step of nD BIM-IKBMS research and development series, concentrating on functional modeling. Notwithstanding which, it is difficult to describe a cross-disciplinary system following a single framework. As the technology evolves, the framework can not be generalized into new scenarios. Towards this end, the study is followed through the complexity theory lens. A highly flexible framework, considering that each part wherein has an opportunity to evolve, was developed. Following the principles of axiomatic design, the proposed framework was established. Ultimately, this research generates a range of detailed 3-hierarchical Icam DEFinitions for Function Modeling 0 (IDEF0) diagrams outlining the proposed nD BIM-IKBMS structure. This study identifies the interoperability of the proposed framework by standardizing communication protocols, data formats, naming convention, evaluation systems, and modulization. While this research is limited to implementing our nD BIM-IKBMS framework, real-world projects will be utilized in our upcoming steps of R&D series for validation purposes.

1. Introduction

Post-construction energy consumption is a demanding issue accounting for a significant proportion of the building's total energy use [1]. Facility management (FM) is regarded as a primary driver for post-construction energy usage. Also, traditional post-construction building inspection solutions are limited [2], e.g., through progress tracking practice via manually recording milestones and specifications [3]. Effectiveness and accuracy of the inspection process can be affected based on the individual's judgment and their observational skills. This emphasizes the need for dominant building management systems (BMSs) [4]. On the other hand, applications of amplified sensor data and improved computational support for building controls are expected to reduce the high proportion of energy consumption in the construction industry [2]. Respectively, it is essential to maximize building energy performance as well as achieve occupant comfort through utilization of an efficient BMS. Appropriate use of such BMS enables detecting faults and sustaining the facility proficiently [5].

Building Information Modeling (BIM) is a leading technology for AEC practices. It plays a vital role in facilitating the project delivery success, especially during post-construction [6,7]. BIM, via multiple dimensional information delivery and coherent data integration, has promoted building energy conservation and sustainable practices [8,9]. Involvement of a robust Knowledge-Based System (KBS), through consolidating the storing and reasoning of respective building maintenance information during the post-construction phase, is expected to take the role of BIM in sustainable missions to the next level.

This study is established based upon on our literature-based foundation proposing the concept of n Dimensional (nD) BIM Integrated Knowledge-based BMS (BIM-IKBMS) [10]. ND BIM-IKBMS refers to a specific Intelligent Building Management System (IBMS) in the AEC/FM industry. Effective capacities of BIM in visualization, informatization,

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standardization, and cooperativity while integrated with the nD BIM-IKBMS concept is anticipated to maximize potentials for optimization of post-construction energy consumption while maintaining occupants' level of comfort. The benefits of proposing nD BIM-IKBMS in maximizing energy efficiency while retaining the occupants' comfort have been identified in our foundation research [10]. Therefore, research objectives in this article are listed as follows:

1. To identify the functional requirements for the proposed system to fulfill the expectations in the previous research.
2. To indicate the key factors which influence the interoperability for the proposed framework.
3. To verify the flexibility of the proposed system towards module replacement.

This research highlights the fundamentals of nD BIM-IKBMS based on axiomatic design principles. Various components of the proposed system are explained in detail. Having completed a state of the art review concerning building energy efficiency, it is suggested that the post-construction energy consumption accounts for a significant proportion of buildings' total energy usage [1,11,12], demonstrating the underlining importance of energy conservation in AEC/FM industry. Considering building construction life-cycle assessment (LCA) is essential for the building energy performance optimization [13]. Facility operation/management is the primary driver for post-construction energy consumption [5]. In this regard, meaningful early-stage sustainable decision making [14], timely and reliable maintenance [15], and attentive occupant behavior [16] are identified as the principal means of such energy optimizations.

This article reconfirms that BIM has excellent potential applicability for effective visualization, computerization, standardization, and integration in post-construction phase. However, current BIM is not well discipline-oriented. Proposing discipline-oriented development, especially for building energy conservation, would mainly extend the use of BIM. Moreover, it supports building energy efficiency. Besides, adoption of BIM during pre-construction phase reduces energy consumption compared to traditional CAD methods [17]. Extensive information is integrated and structured in BIM models such as 3D entities, schedules, estimation, sustainability and FM [18]. In the same direction, an integrated BIM platform is anticipated to help dynamize and standardize the conventional methods of building energy conservation.

Due to the oversimplification of occupants' behavior during building design and retrofitting evaluation [19], the associated real-world uncertainties of their behaviors should be considered [20,21]. These uncertainties are categorized into aleatory uncertainties (occupant, appliance operation, and window/shading operation) [21] and systemic uncertainties (accuracy of analysis tools, the authority of data collected the rationality of model simplification) [19]. The need to confront these dilemmas propelled the development of pre-construction and post-construction simulations that support early decision making and process evaluation, respectively.

This article begins with an introduction to raise three objectives from the subject background. The significance of this research has been demonstrated in our literature review [10]. The remaining part of the paper proceeds as follows: In the second part, the complexity theory is introduced to examine the topic through; the third part is concerned with the axiomatic design approach used for this study; the fourth part presents the framework formation of the research, focusing on the five modules from a multi-level/option perspective; the fifth part analyses the factors that influence the interoperability of the proposed system; in the sixth part, the flexibility of the proposed system is verified; finally conclusions are drawn on the response to the original objectives.

2. Theoretical and conceptual framework

2.1. Theoretical framework

This study intends to improve the efficacy of building operation and maintenance (O&M) information management. To achieve this, a resolution for solving the information peculiarity and fragmentation issues should be developed and then evaluated. It is generally agreed that the technology is developing rapidly. This phenomenon brings two barriers for developing such resolution:

First, the technology used in part of the whole resolution is continually evolving by itself. A simple system cannot be flexible enough to this change as the parts inside are interacted with each other. To put it into another way, a new-developed resolution might be quickly faded out when one of the technologies it uses evolves. This largely reduces the implications of the development.

Second, the resolution to the research problem is cross-disciplinary. Provide that, the pre-condition of successfully developing it was to transform such "cross-disciplinary" into "multi-disciplinary." Such "multi-disciplinary" resolution contains a number of levels or scales. Each individual basic unit should only involve one single academic field. A single academic field refers to the branch of knowledge that a typical individual researcher or engineer in the real world is capable of achieving.

Regarding these matters, the resolution is complicated. In the literature, there are numbers of ways where a system is identified complex. Senge [22] noticed that "a system presents dynamic complexity when cause and effect are subtle, over time." Based on the earlier discussion our resolution presents dynamic complexity in the evolution of the technology within parts of it. Meanwhile, the various parts and their interactions exacerbate the complexity degree. This has been confirmed by Sussman [23], noticing that "a system is complex when it is composed of a group of related units (subsystems), for which the degree and nature of the relationships are imperfectly known." Also, Joel Moses indicated that "a system is complex when it is composed of many parts that interconnect in intricate ways" [24]. Therefore, our proposed resolution should be examined as a complex system.

Towards this end, the "complexity" theory was adopted as the lens to examine this topic throughout the whole research process (see Fig. 1). Refer to Mikulecky [25], "complexity is the property of a real-world system that manifests in the inability of anyone formalism being adequate to capture all its properties." It provides an insight into the real-world systems and their scales. From a complexity perspective, this study should scale the system to its parts and then study those parts in a context formulated according to dynamics [26]. There are two main benefits of doing this.

First, transform the research problem from a cross-disciplinary into a multi-disciplinary perspective. The proposed resolution was divided into parts. For developing every single part, a unique discipline knowledge is needed, so that the parts can be developed by different people or organizations. When adopting it, all they need to do is to integrate them together. While the relationship between each part was already defined based on the complexity theory.

Next, when one part evolves, the other parts are highly flexible to this change. All parts of the system are independent in form although they can interact with each other by sending or receiving information from each other. All parts should be well developed alone while the interface between each interacted part was standardized. Rather than entirely replacing the old system, a new system is updated in a way that a new part developed following the interoperability rules replaces the old one.

2.2. Conceptual framework

To scale the system into basic units and then study them in a context formulated according to the dynamics, a conceptual framework of the

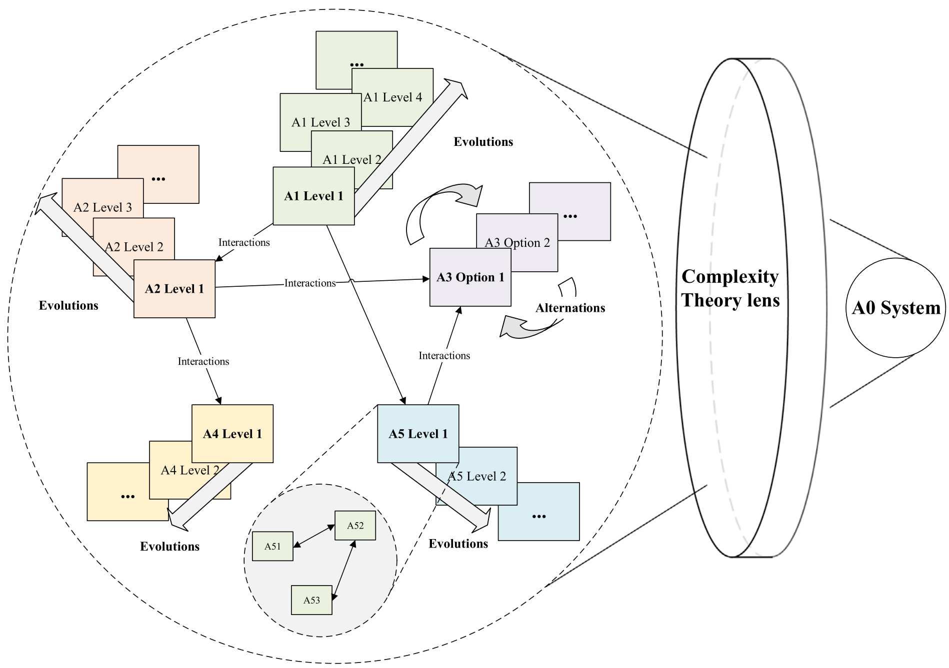

Fig. 1. Visions of this study through the "complexity" theory lens.

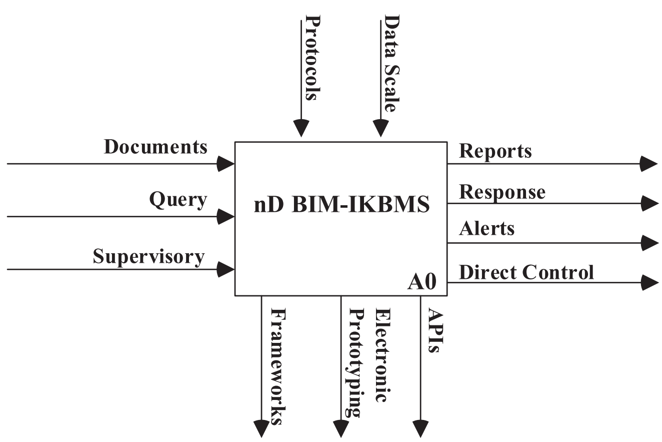

Fig. 2. Conceptual framework: the nD BIM-IKBMS model.

proposed resolution was established. The proposed resolution adopts an nD Building Information Model Integrated Knowledge-Based Building Management System (BIM-IKBMS) as its theoretical framework. The significance of proposing such a system has been validated by GhaffarianHoseini [10]. It was demonstrated that the proposed system is capable of improving the efficacy of building O&M information management. As illustrated in Fig. 2, the inputs, outputs, tools, and constraints of the nD BIM-IKBMS model are identified.

The proposed system has three types of inputs:

- It integrates construction handover documents, as-built BIM models, and other documents required for operating and maintaining a building. It works as a database for all the corresponding building data;
- It carries on reasoning based on the query input. Whenever the FM people have a situation, the proposed system can be retrieved for maintenance solutions. The situation can be an operation error, or even a pipe corroded.
- The end users supervise the proposed system for managing the direct control. It can be directly given the command for direct control or strategically adjust the operation mode by changing the event listeners.

The proposed system has four types of outputs:

- The proposed system generates building performance simulation reports to the end users. The results from such reports can be used for predicting the energy consumptions under designated conditions. This can facilitate the decision-making processes for O&M.
- The proposed system responds to the query with solutions retrieved from its knowledge base. Such solutions will guide the FM people step by step for sorting the problem out. After that, the knowledge base will be updated by rating the retrieval results by the FM people;
- The proposed system alerts the FM people for asset warranty expired, illegal operation or any other faults detected. Wherein, the typical flaws can be principled paired with their location and directly send to the retrieving system once occurs. Besides, the untypical flaws will be updated into the proposed system by the end users for future fault detection.
- The proposed system sends the commands for directly controlling the devices. Such commands are made either straight from the end-user input or by an event listener who keeps on monitoring the sensors.

The proposed system has three types of resources:

- It can adopt an existing framework for developing the software or deploying the hardware. As mentioned before, a SCADA framework can be used for supervisory control and data acquisition. Wherein, the level of such a framework should be designated. With the rapid development of SCADA technology, the fourth level of SCADA – the Internet of Things (IoT) is more and more popular used all over the world.
- It can be developed based on several off-the-shelf APIs. To visualize the building information, Autodesk Forge APIs are generally used globally. It packages an expanding collection of web service components that can be used with Autodesk cloud-based products. It saves time from programming repeatedly for the existing UI functions. Instead of depending on APIs whose intelligent property (IP) owned by other organizations, open source libraries such as

OpenGL, WebGL are preferred for interacting with a graphic processing unit.
- The proposed system can be tested in electronic prototyping. There are numbers of open-source electronic prototyping platforms such as Arduino, Raspberry Pi, and so on. The proposed system can be easily programmed and rapidly prototyped by using these platforms.

The proposed system has two types of constraints:

- The hardware deployed in the proposed system should be configured with the right serial communication protocol. Serial communication happens when sending data one bit at a time sequentially over a communication channel or computer bus. There are various protocols such as Modbus series. They are usually used to connect a supervisory computer with a remote terminal unit (RTU) in a SCADA system. On condition that the protocols are developing and updating as well.
- The efficacy of the proposed system is limited to the data scale it faces. Take operational fault monitoring as an example; the FM people might be dropped down when it keeps on receiving thousands of alerts every second.

Above all, the conceptual framework established here is a functional overview. To put it in another way, it is a general function design with inputs, outputs, tools, and constraints (Cs). However, it still depends on cross-discipline technology. Based on the complexity theory, the proposed conceptual framework should be deepened into more basic units.

3. Research methodology

Based on the complexity theory, the proposed resolution should be modulized into basic units which only contains single discipline knowledge. While, these units should be independent in its forms. To satisfy both of these requirements, an axiomatic design approach was adopted to develop the nD BIM-IKBMS conceptual framework. Refer to Suh [27], "Axiomatic design is a systems design methodology using matrix methods to systematically analyze the transformation of customer needs into functional requirements, design parameters, and process variables." Such an approach provides a scientific base for system research and development that supports the creativity of designers. Additionally, it reduces the random searching process, shortens the iterative process of trial and error, clarifies the assessment principles of design, and endows the computer with the capacity to create [28]. This proposed system was designed based on *independence axiom*, *information axiom* and their inferences for axiomatic design. By following the independence axiom, the proposed system can be highly flexible for the evolution of its parts. Besides, with the information axiom, the best scheme can be selected. Provided that, this study should meet the requirements of the independence axiom, however, the information axiom will be left as a principle for future study to refine this system.

Integrated Computer-Aided Manufacturing DEFinition for Function Modeling (IDEF) is a function modeling methodology that consists of a hierarchical series of diagrams, text, and glossary cross-referenced to each other [29]. By using IDEF0, this study can conduct an axiomatic design for reducing the complexity of the proposed system. A typical IDEF0 box used in this study has been illustrated in Fig. 3. As we can see from the illustrations, Structured Analysis and Design Technique (SADT) language is used in IDEF0 to describe the proposed system. Such diagrams are used to define the proposed functions while arrows are used to identify the relationship between these diagrams [30].

As discussed above, this study followed the complexity theory and designed the proposed system by using axiomatic design approach with IDEF0 tools. The research process for this stage has been illustrated in Fig. 4. Before commencing this stage, a focus group interview was done for filtering the specific barriers paired with their specific suggestions.

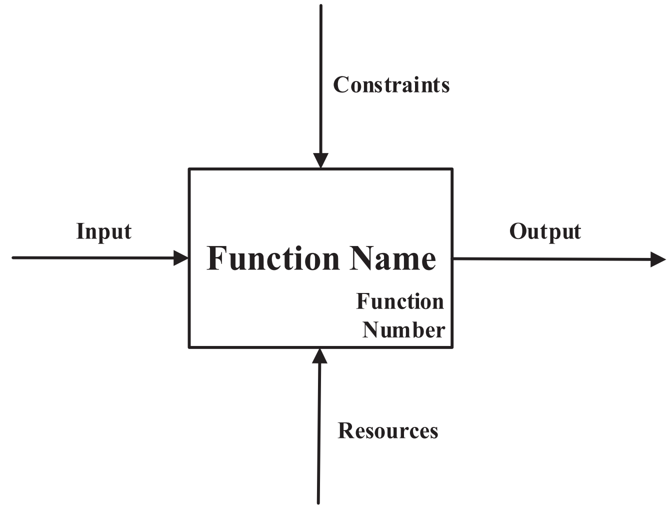

Fig. 3. IDEF0 box used in this research (adapted from Leonard [30]).

Based on this information, the customer attributes (CAs) were determined; after that, the mapping between CAs and Function Requirements (FRs) was carried on. The functions for the proposed system have been determined; next, this study aligned Design Parameters (DPs) to these FRs. The functional models were built, and this article was concluded at this step; in the next article, the relationships between FRs and Process Variables (PVs) will be linked while working prototypes were developed and tested; meanwhile, the design scheme should be verified by independence axiom while evaluated by using information axiom. To make this research sustainable, a refined design in the future is welcome. Once the new scheme shows the less information content while maintaining the independence features, the old scheme can be replaced by the new one. The design in this study should satisfy the independence axiom to maintain the flexibleness for each part of the proposed system. Despite this, the information content of the proposed system should be further optimized based on the information axiom in the future.

4. ND BIM-IKBMS (framework formation)

To improve the efficacy of building O&M information management, inspection and optimization of sustainable performance during post-construction has become increasingly essential. However, conventional operation and maintenance processes are limited with a high probability of inaccurate manual building inspections and the lack of real-time input of dynamic factors. Data collected in the qualitative phase indicated that engagement of a KBS facilitated BMS using nD BIM applications is anticipated to promote promising resolutions. Following the literature-based conceptual model developed, this section aims to generate and verify the proposed framework, concentrating on functional modeling. This study follows principles of axiomatic design and develops the proposed framework in SADT language using IDEF0 diagrams. To obtain a highly flexible complex system, we considered the evolution for each module and indicated the mutual interactions. Ultimately, this research generates a range of detailed 3-hierarchical Icam DEFinition for Function Modeling 0 (IDEF0) diagrams outlining the proposed nD BIM-IKBMS framework. This study identifies the capability to reduce post-construction energy consumption when utilizing intelligent controls and historic retrievals. The system was verified through efficiency demonstration based on the Independent Axiom.

The proposed system (A0) has been divided into five modules (see Fig. 5). They are:

- A1 Building Automation System (BAS) module

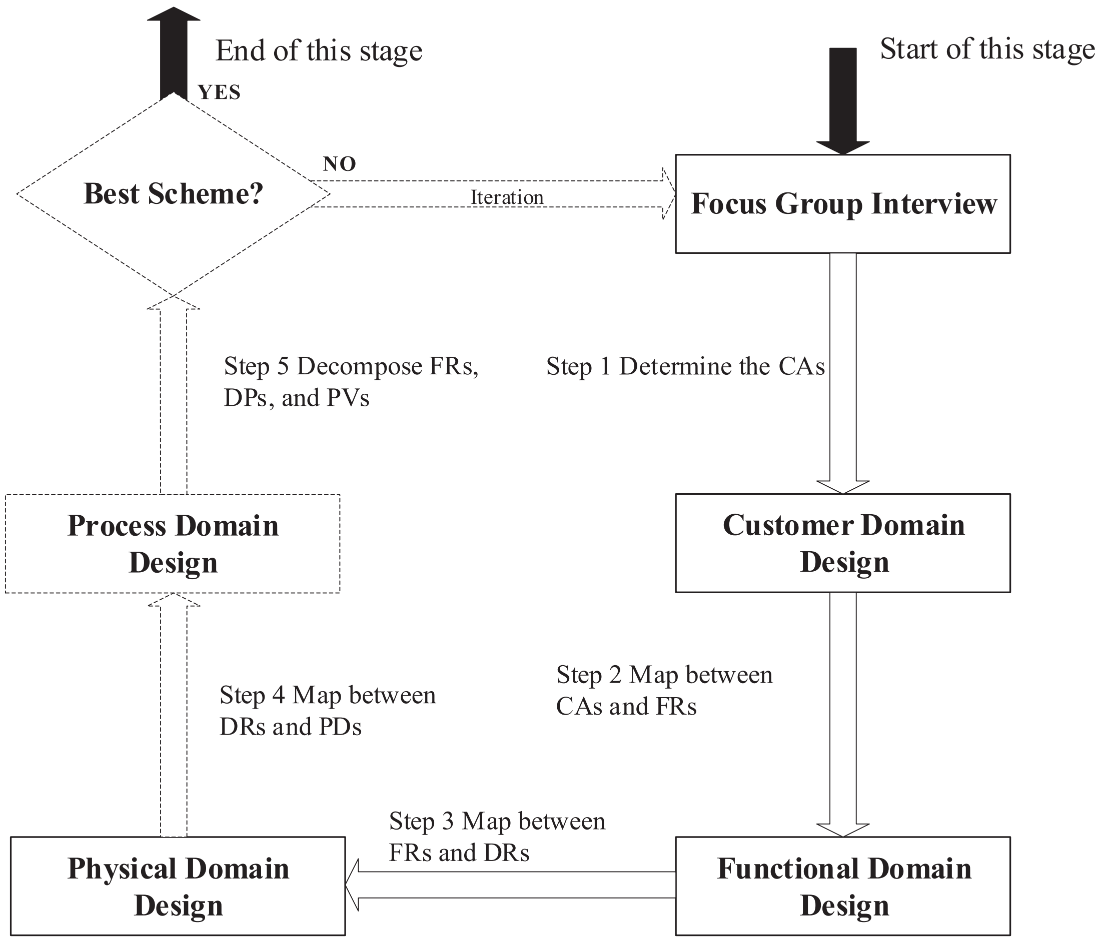

Fig. 4. Research process in the design stage.

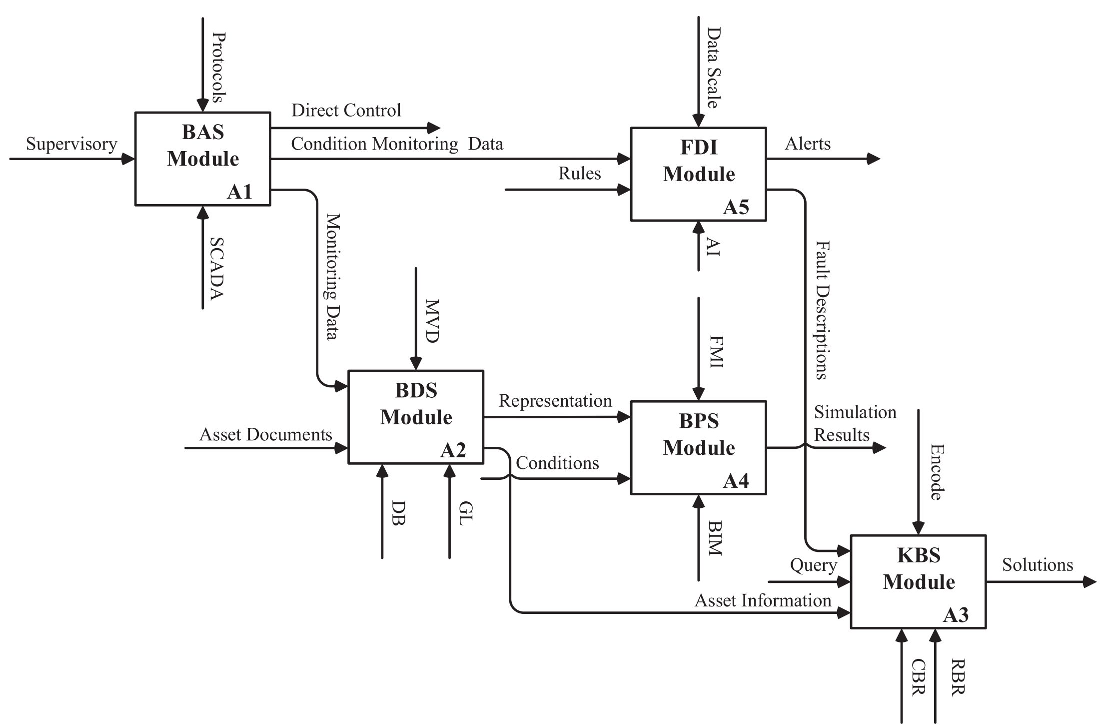

Fig. 5. A0 ND BIM-IKBMS module division.

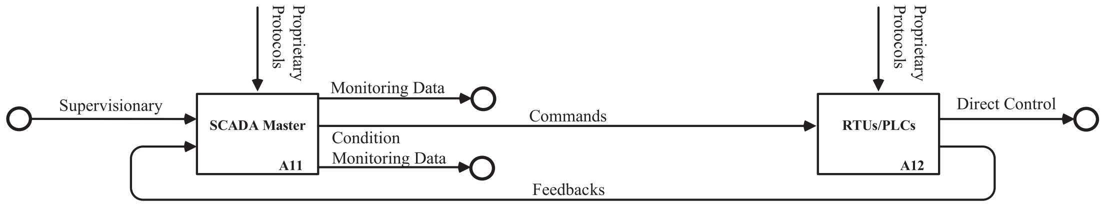

Fig. 6. A1 BAS module (level 1 monolithic) sub-module division.

The function of the A1 BAS Module was developed upon the existing BASs within a SCADA framework. This module receives supervisory commands from the end users while outputs direct controls to the facilities connected. Any pair of the facilities within this module should follow the same communication protocol when interacting. Once operated, the conditions for the facilities whereby were monitored and the monitoring data will be sent to the Fault Detection and Isolation (FDI) Module.

- A2 Building Description System (BDS) module

The function of the A2 BDS Module was adapted from the building documentation methods utilizing database technology and graphic libraries. Assets documents are imported into this module. To facilitate the interoperability, the models in this module should follow the IFC standards. Refer to buildingSMART International Ltd. [31], "Industry Foundation Classes (IFC) are the open and neutral data format for openBIM." Such format is an official International Standard ISO 16739:2013 registered by International Organization for Standardization [32]. Based on such format, the building representation including the assets documents and digital models is exported to be used in A3 KBS Module and A4 Building Performance System (BPS) Module separately.

- A3 KBS module

The function of the A3 KBS Module was assigned with use of existing KBSs. There are mainly two types of KBS which are used in this study: Case-Based Reasoning (CBR) and Rule-Based Reasoning (RBR). They all utilize KB languages to retrieve solutions for each query. Such queries include manual queries from the end users and the automatic queries from A5 FDI Module. The automatic queries will be in a format of fault description so that the efficiency of such reasoning processes can be enhanced. To assist such retrieval, asset information is also collected from A2 BDS Module.

- A4 BPS module

The function of A4 BPS Module laid on the conventional BPS software solutions. As 3D models are required in simulating building performance, most of them can be facilitated by BIM. Coupled with the conditions input by the end users, reusing BIM models from A2 BPS Module can significantly reduce the costs from repeating modeling processes. The simulation results will be reported to the end users for decision-making in O&M. Particularly, standard interfaces are adopted for exchanging the building performance simulation data among multiple software.

- A5 FDI module

The function of A5 FDI Module was designed upon the conservative FDI solutions. Artificial Intelligence (AI) algorithms are used to recognize the faults from the condition monitoring data imported from A1 BAS Module. The rules should be designated by the end users. Once faults are detected, this module will alert the end users while sending the fault descriptions diagnosed to the A3 KBS Module for similar case retrievals.

4.1. Building automation system (BAS) module

To support the supervisory control, a Supervisory Control and Data Acquisition (SCADA) framework was adopted. With the development of such framework, four SCADA levels exist in the industry. By adopting different SCADA levels, the proposed system can put on different interoperative performance.

4.1.1. A1 BAS module (level 1 monolithic)

At the first SCADA level, "mainframe" systems were adopted without networks. Such SCADA system is independent of each other. Besides, such a system is constrained by the proprietary protocols developed by various RTU vendors. The proposed system has two types of devices: A11 SCADA Master Sub-Module and A12 RTUs/PLCs Sub-Module. The master is capable of acquiring streaming data from sensors while reporting the condition monitoring data; while the terminal devices can carry on a direct control for the facilities while sending feedbacks to the A11 SACADA Master. Despite this, the A11 SCADA Master Sub-Module were most commonly connected at the bus level via a proprietary adapter or controller plugged into the Central Processing Unit (CPU) backplane. The sub-module division has been illustrated in Fig. 6. Each module wherein conducts mutual interactions which make the sub-module dependent inside. Hence, it cannot be further divided.

4.1.2. A1 BAS module (level 2 distributed)

When the Monolithic evolved, a "distributed" system was then adopted. With the help of system miniaturization and Local Area Networking (LAN) technology, the proposed module distributed the processing across multiple systems. Several stations (A11 Operation Stations Sub-Module) were connected through a LAN for sharing information with each other in real time. Each station has its own functions and communicates with its A12 Communication Servers Sub-Module coupled with their A13 RTUs/PLCs Sub-Module. Meanwhile, the system reliability was increased by adding more redundancy. Once one station down, the others can be alternatively used to operate the system. However, such distributed networks increased the processing power requirements. Besides, the external communications networks were merely constrained by various RTU protocols. To put it into another way, the BAS module at this level was still limited in a vendor controlled, proprietary environment. The sub-module division has been illustrated in Fig. 7. Each module wherein conducts mutual interactions which make the sub-module dependent inside. Hence, it cannot be further divided.

4.1.3. A1 BAS module (level 3 networked)

Facing the issues mentioned above in the distributed SCADA, a Networked module was then introduced. Compared to the previous generation; an open system architecture was utilized at this level for eliminating the limitations of the various vendors. This module adopts open standards and protocols which opens up to distribute SCADA functionality through a wide area network (WAN). With the help of WANs, A14 Networked Remote Terminal Units (RTUs)/Programmable

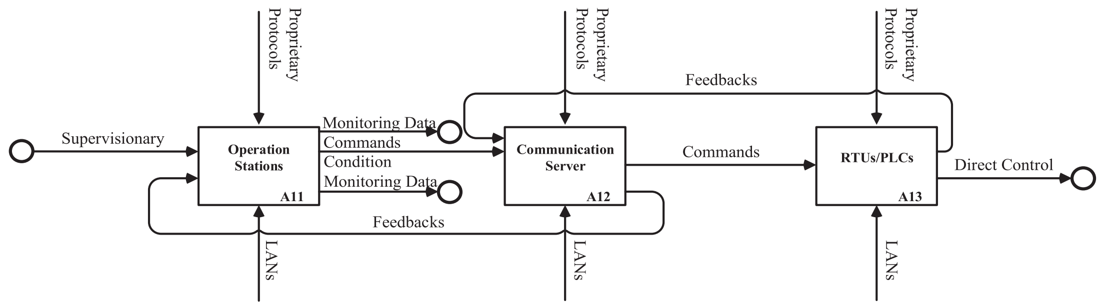

Fig. 7. A1 BAS module (level 2 distributed) sub-module division.

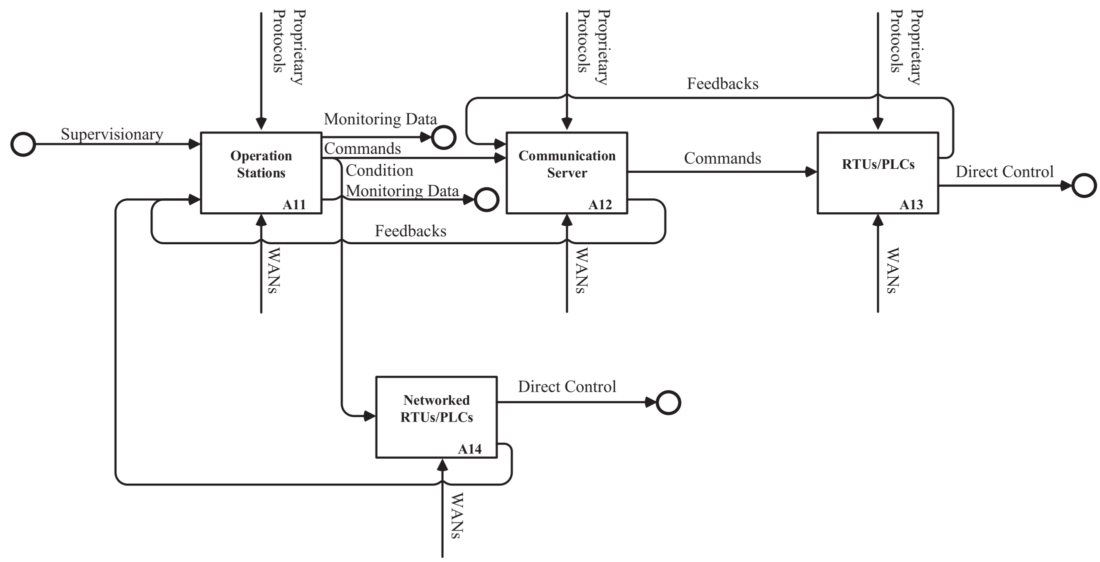

Fig. 8. A1 BAS module (level 3 networked) sub-module division.

Logic Controllers (PLCs) Sub-Module were directly connected with the A11 Operation Stations Sub-Module. Nevertheless, vendor-proprietary RTUs still existed at this level. Provided that A12 Communication Server Sub-Module was still used for communicating such vendor-proprietary RTUs. Also, the module distributed the processing into several individual physical locations. This largely increases the system reliability upon the previous generation which stored data in separate devices but in a single location. The sub-module division has been illustrated in Fig. 8. Each module conducts mutual interactions which make the sub-module dependent inside. Hence, it cannot be further divided.

4.1.4. A1 BAS module (level 4 IoT-based)

Towards putting this module into a higher level, an IoT-Based evolution was continued. At this level, the operation stations were replaced by A11 Cloud Server Sub-Module. All vendors adopted an ISO protocol. This agreement makes it possible for communicating among all devices. The A11 Cloud Server Sub-Module can send commands to or receive feedback from either A12 Communication Server Sub-Module or A13 RTUs/PLCs Sub-Module. A12 Communication Server Sub-Module is used for privacy considerations where an additional setting can be configured. Also, the condition monitoring data will be sent for fault detection. The sub-module division has been illustrated in Fig. 9. Each module wherein conducts mutual interactions which makes the sub-module dependent inside. Hence, it cannot be further divided.

4.2. Building description system (BDS) module

To manage and maintain the asset information, a documentation framework was designed. Such a framework provides a representation for the BPS Module. With the development of such a framework, three documentation levels exist in the industry. In different documentation levels, the proposed system can associate with different interoperative behaviors.

4.2.1. A2 BDS module (level 1 flat files)

At the first level, flat files were used for storing asset documents. Based on this method, A21 Database Sub-Module is short of internal hierarchy which is inefficient in retrieving the information. The MVD used for constraining this module was merely flat files database specifications. Pictures were documented through pixel-based graphic tools. No 3D models were created at this level. That means, User Interactions were needed to establish the representation (models) for performance analysis in A4 BPS Module. The sub-module division has been illustrated in Fig. 10. Due to the functional independence, these submodules can be further divided. Despite this, this study did not intend to carry on further division as each sub-module represents a single discipline problem.

In recent decades, the use of CAD led to an evolution in building design documentation (A22 Computer-Aided Document Management Sub-Module). At this level, vector-based graphic tools facilitate the accuracy of the drafting. Hence, 2D representation was commonly produced. Despite this, numbers of BPS solutions which require 3D representation. This raised the demand for User Interaction for generating 3D representation based on the 2D representation maintained by A22 Computer-Aided Document Management Sub-Module. Meanwhile, a relational database or navigational database (A21 Database Sub-Module) was adopted at this level. Compared to the flat

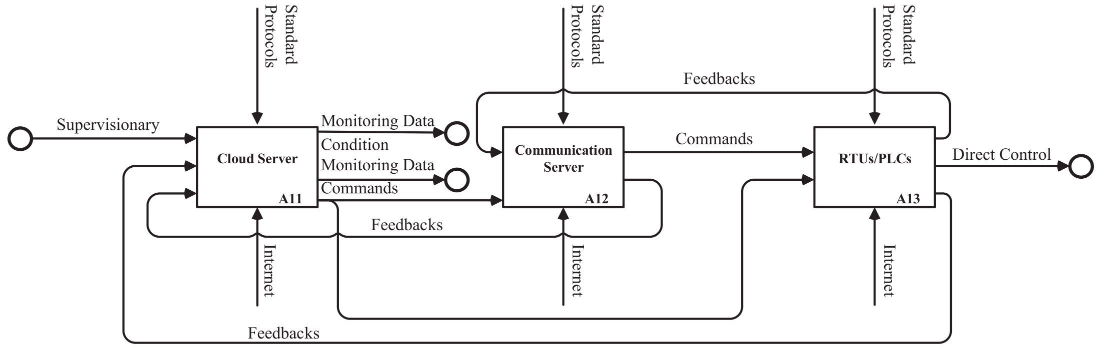

Fig. 9. A1 BAS module (level 4 IoT-based) sub-module division.

files database, such databases were easier for retrieval information through a well-defined inner hierarchy. Also, the MVD at this level was mainly the 2D drafting specifications. Provided that, such specifications were client-proprietary. That is to say; no common standardized MVD was used at this level. The sub-module division has been illustrated in Fig. 11. Due to the functional independence, these sub-modules can be further divided. Despite this, this study did not intend to carry on the further division as each sub-module represents a single discipline problem.

4.2.2. A2 BDS module (level 1 object-oriented)

When achieving the object-oriented level, a BIM-based platform was centralized. Such platform holds an object-oriented architecture for data storage. Elements were stored and retrieved through a globally unique identifier (GUID). All the information related to an individual component should be stored under its GUID. Such information includes but is not limited to 3D entities, 4D time (scheduling), 5D costs (estimation), 6D Post-Construction Lifecycle Information. Compared to the previous generations, such level of use can process the representation needed independently. Besides, Construction Operations Building information exchange (COBie), as a standard MVD for construction operations, was adopted where IFC format was used. The sub-module division has been illustrated in Fig. 12. Due to the functional independence, these sub-modules can be further divided. Despite this, this study did not intend to carry on the further division as each sub-module represents a single discipline problem.

4.3. Knowledge-based system (KBS) module

To retrieve the similar case when faults occur, a reasoning framework was ruled. Such a framework provides the solutions from similar cases for the FM managers. With the development of such framework, two optional rules exist in the industry. By using different rules, the knowledge base can perform different sustainability.

4.3.1. A3 KBS module (option 1 case-based)

CBR was used for capturing lessons from past problem-solving experiences to critique or finding solutions to new problems. Before conduct the reasoning, the fault descriptions or queries should be characterized in A31 Case Characterization Sub-Module. Typically, two components were deployed: a case library (A33 Case Base Sub-Module) and an inference cycle (A32 Inference Engine Sub-Module). A32 Inference Engine Sub-Module is capable of retrieving, reusing, revising and retaining cases directly from or to A33 Case Base Sub-Module. As the cases were stored flatly and retrieved on its characters, A33 Case Base Sub-Module was easy to maintain by the end users. Towards this end, a user-profile score was commonly utilized for maintaining the A33 Case Base. Significantly, a standard built environment classification system should be used. With the help of such a classification system, the efficiency of the retrieving processes can be largely improved. The sub-module division has been illustrated in Fig. 13. Each module wherein conducts mutual interactions which makes the sub-module dependent inside. Hence, it cannot be further divided.

4.3.2. A3 KBS module (option 2 rule-based)

Alternatively, an RBR method was also popularly used in industry. Compared to the case-based A3 KBS Module, such option performed more automated as an explicit model was established in A33 Rule Base while A34 Case Base was indexed by rules. However, such A34 Case Base can hardly be maintained by the end users except keeping on revising the rules. The sub-module division has been illustrated in Fig. 14. Each module conducts mutual interactions which makes the sub-module dependent inside. Hence, it cannot be further divided.

4.4. Building performance system (BPS) module

To provide a supervision control for the A1 BAS Module, a performance simulation was conducted. Such a simulation provides the energy simulation results for the FM managers. With the development of such a framework, two levels of use exist in the industry. By adopting a higher level of BPS, the hardware loads can be largely reduced.

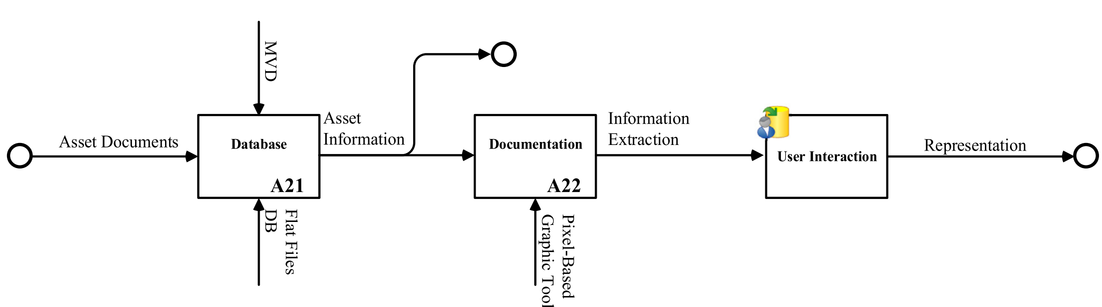

Fig. 10. A2 BDS module (level 1 flat files) sub-module division.
(2) A2 BDS module (level 1 computer-aided).

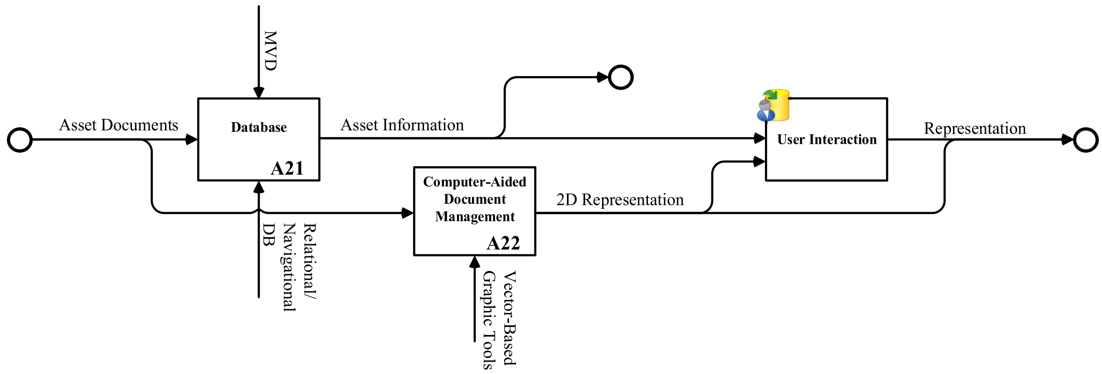

Fig. 11. A2 BDS module (level 1 computer-aided) sub-module division.

4.4.1. A4 BPS module (level 1 stand-alone)

Before commencing the simulation, the representation input was pre-processed. Some of them were exported from BIM while others were modeled manually. Conventional BPS solutions were installed merely on PCs. The processes (A42 Calculation Sub-Module) were constrained by the hardware configuration. As a result, the value grids or lists were obtained and imported into A43 Contour Plotting Sub-Module. When conducting contour plotting, the values were translated into RGB values. Such RGB values were rendered onto the meshes obtained from A41 Pre-Processing Sub-Module. The results of this process were output to the end users. Besides, such framework can facilitate the certifications for the green building evaluation systems, whereas green building evaluation systems can standardize the assessment process within A4 BPS Sub-Module efficiently. The sub-module division has been illustrated in Fig. 15. Due to the functional independence, these sub-modules can be further divided. Despite this, this study did not intend to carry on the further division as each sub-module represents a single discipline problem.

4.4.2. A4 BPS module (level 2 cloud-based)

Towards a higher efficient hardware configuration, the computing processes were put into the cloud. The digital representation coupled with the conditions was sent to the cloud server (A42 Cloud), and the end users would receive simulated results in a short time. This also makes real-time dynamic simulation possible whereas the previous generation can only provide stand-alone processing. Notably, Functional Mock-Up Interfaces (FMI) was used for standardizing the simulation at this level. FMI is an independent tool standard to support both model exchange and co-simulation of dynamic models. The sub-module division has been illustrated in Fig. 16. Due to the functional independence, these sub-modules can be further divided. Despite this, this study did not intend to carry on the further division as each sub-module represents a single discipline problem.

4.5. Fault detection and isolation (FDI) module

To detect the operational faults, an FDI process was carried on. Such a method identified the flaws from the condition monitoring data and output the fault descriptions to A3 KBS Module. With the rapid development of FDI technology, two levels of use exist in the industry. By adopting different levels of BPS, the fault response time was much different.

4.5.1. A5 FDI module (level 1 process history-based)

The A5 FDI Module aimed at finding the operation faults and alerting the end users with corresponding information. The most commonly used method was processed history-based. By using the Box-Cox transformation, the conditional monitoring data was pre-processed in A51 Data Pre-Processing Sub-Module. The correlation indices (CIs) were output. Coupled with these CIs, algorithms, such as QTA, PCA, PPCA, PLS, and Neural Networks, were typically used for the recognition of the unusual signals. Once found, the reconstruction-based contributions (RBCs) were sent to A53 Isolation Sub-Module. By analyzing those RBCs, the A53 Isolation Sub-Module was expected to obtain the possible fault classification paired with locations. Towards this end, Neural Networks, Statistic Classifiers were used. Meanwhile, it would be more efficient to diagnosis the faults by adopting an expert system. Despite this, an expert system already existed in A3 KBS Module. To maintain the functional independence of A5 FDI Module, we assign these functions into A3 KBS Module. The sub-module division has been illustrated in Fig. 17. Due to the functional independence, these sub-modules can be further divided. Despite this, this study did not intend to carry on the further division as each sub-module represents a single discipline problem.

4.5.2. A5 FDI module (level 2 real-time)

In the first level, the fault response time was too long. As the historical process data should be obtained before conducting the detection and isolation. Given this, a higher level of responsive A5 FDI Module was developed. Rather than waiting for the history process data been

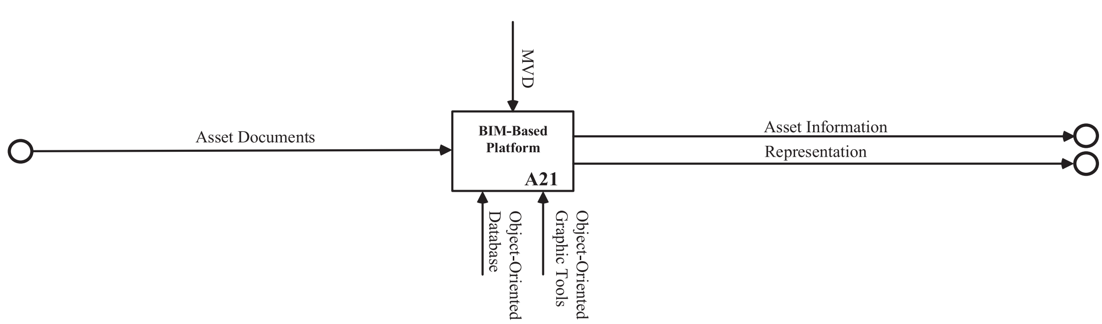

Fig. 12. A2 BDS module (level 1 object-oriented) sub-module division.

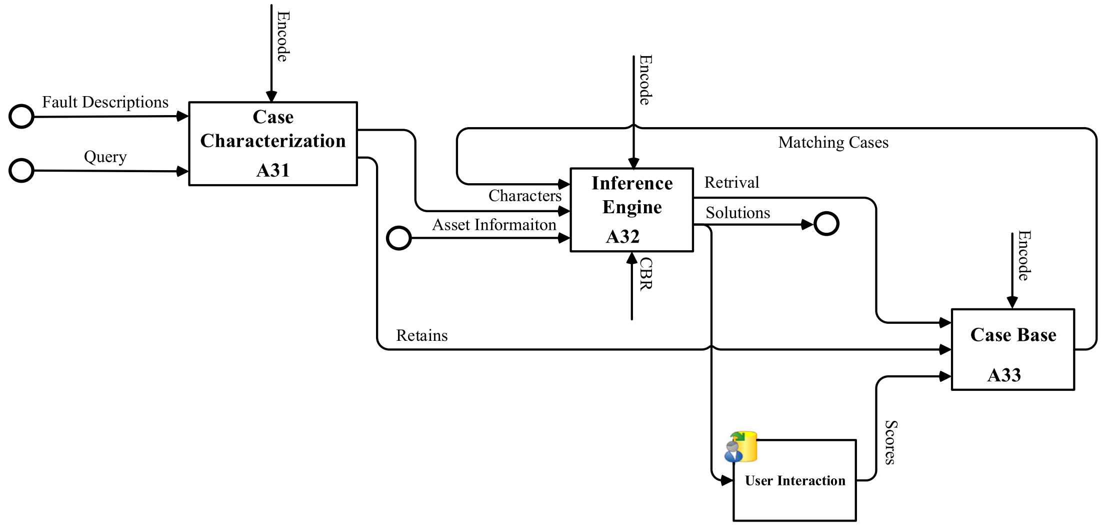

Fig. 13. A3 KBS module (level 1 case-based) sub-module division.

collected, such level of FDI is capable of processing real-time condition monitoring data. Assisted with algorithms including EKF, Parity Space, and Observers, A52 Detection translates those CIs into RBCs. Algorithms such as Digraphs, Fault Trees, and Qualitative Physics were run for classifying and locating the faults. Such level of FDI performs more sensitive to the operational faults. However, the data scale often overloaded the hardware on processing these data in real time. Whereas, insufficient data sets might lead to the disturbance in results due to the data noise. The sub-module division has been illustrated in Fig. 18. Due to the functional independence, these sub-modules can be further divided. However, this study did not intend to carry on the further division as each sub-module represents a single discipline problem.

5. Interoperability

Towards a high interoperable framework, the diversity of data formats and protocols presents one of the most significant barriers. By adoption of more than one formats, the representation must be remodeled when transforming from one platform to another. Likewise, operating devices following different communication protocols increase the complexity level of implementing such a framework. Additionally, the variety of naming convention system in the built environment causes the confusion, especially in the scenarios when one organization attempts to retrieval information from the documents created by another organization. This is even worse when retrieving knowledge from past cases as the knowledge are established under different name convention system. In light of this, one of the best strategies for maintaining interoperability in our framework is adopting standards.

5.1. Standard communication protocols

One major issue in early embedded system research concerned the diversity of communication protocols became one of the most significant challenges for system integration [33]. Traditional BASs (SCADA Levels 1–3) were most commonly adopting proprietary protocols. Proprietary protocols are typically developed by the vendors for their devices. Such vendor-proprietary protocols mainly increased the complexity when interoperating multi-vendor systems. Compared to proprietary protocols, standard protocols are more "open." When achieving SCADA Level 4, vendors were aligning their device with standard protocols. Such non-vendor-specific protocols are agreed and accepted by the whole industry. Once, all devices communicate in a single standard protocol; the interoperability is mostly improved. Typical IoT centralized protocols include Message Queuing Telemetry Transport (MQTT) and Constrained Application Protocol (CoAP). Both of them are machine-to-machine (M2M)/IoT connectivity protocols. MQTT was designed as an extremely lightweight publish/subscribe messaging transport. It is efficient to be used for connections between remote locations with low/unreliable bandwidth or limited processor/memory resources. Whereas, CoAP was utilized for communicating in low-powered and lossy networked environment. Therefore, by

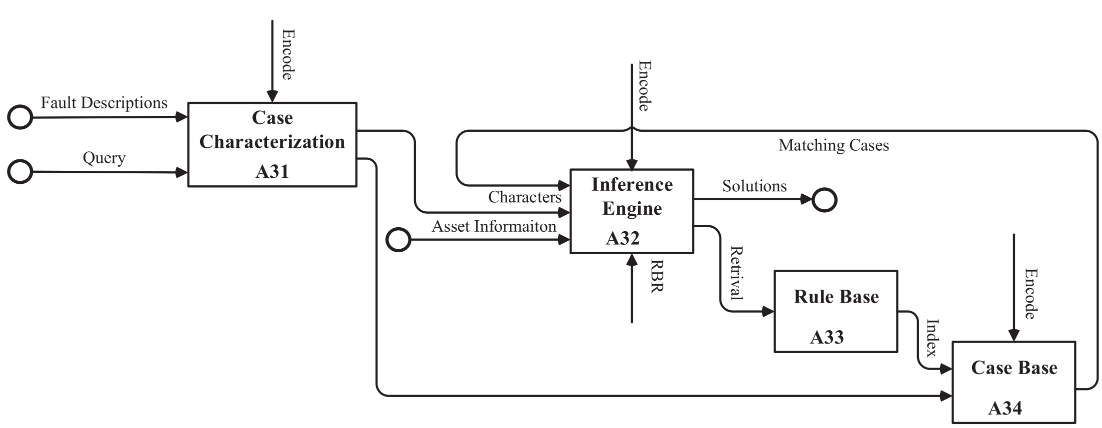

Fig. 14. A3 KBS module (level 1 rule-based) sub-module division.

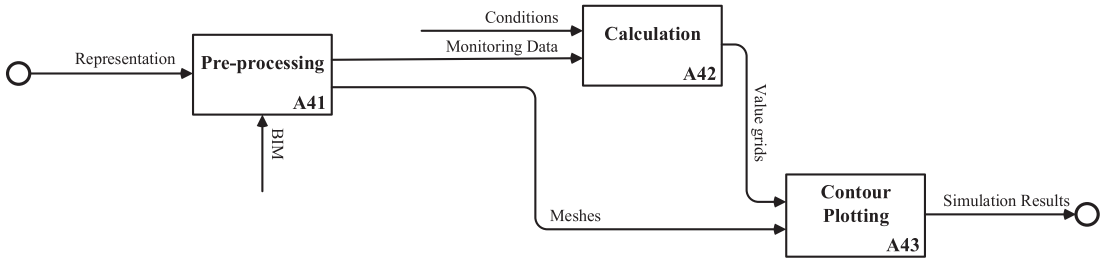

Fig. 15. A4 BPS module (level 1 stand-alone) sub-module division.

standardizing the communication protocol, it becomes more efficient to add or remove an additional part of the whole system.

5.2. Standard data formats

The literature on data exchange in the AEC/FM industry has highlighted several popular used data formats. As mentioned in Andriamamonjy, Saelens and Klein [34], gbXML is a flexible, open, straightforward industry supported data schema for sharing building information between disparate building design software tools. Compared to gbXML, IFC holds a wider scope beyond building design [35]. For our purpose in facilitating post-construction efficiency, IFC was selected as the data exchange format. Wherein, the IFC 4.0 reference view is capable of being applied in most of the common BIM coordination tasks in the current practices. Compared to the previous versions such as IFC 2 × 4, such standard is better specified and more filtered. Also, the standard is ISO certified. Given this, IFC 4.0 was adopted as the data exchange format. In spite of that, current IFC practice still suffers from incomplete information delivery. Errors occur even if both IFC translators are compliant [36]. Some information has to be added manually to full fill the specific function requirements [34]. Taking HVAC system, for instance, performance curves, one of the most important features presenting the various behaviors of a component at each condition, are still missing in IFC4 [37].

Nonetheless, not all the information needs to be exchanged when interoperating. The requirements for this are variations among different objectives. For each exchange, the required information is named as a Model View Definition (MVD). COBie is one of those MVDs, which specializes in space and equipment. Such MVD provides an Excel spreadsheet of all the assets kept and managed in a building. Based on COBie, the facility information can be standardized in the design stage, most commonly when modeling in Revit. However, the majority of BIM tools which follows the MVD in their exporting processes still require individual elements and relationships to be mapped to IFC classes manually, which makes the process easily be taken in human errors and omissions [38]. This arises the need for a more specific MVD for the proposed system. When interoperating with other modules, several IFC types were used: IfcPerformanceHistory, IfcPropertySet, IfcPropertySetTemplate, IfcRelAssociateClassification, IfcController, IfcAlarm, IfcEvent, IfcProcudure, IfcTask. The building facility entities have already been included in the IfcDistributionElement while the real-time state is stored in IfcPerformanceHistory. IfcRelAssociatesClassification contains the URLs of gateways and addresses of devices and data points. Such IFC type is efficient to identify the control elements. With the help of such classification, the performance history can assign to the corresponding control elements. Despite this, IFC 4.0 does not specify BMS protocols. Those protocols can be mapped to standard protocols or vendor implementations for commissioning and operations interoperability.

When conducting real-time simulation in the BPS module (Level 2), multiple software solutions might be joined together to obtain the results. A standard FMI was adopted to facilitate simulation data exchange. Such standard was verified efficient in IEA EBC Annex 60 report on coupling different simulation tools for data exchange during run-time and for real-time simulation [39]. Such report provided a blueprint of the new generation of computational tools for the design and operation of the building and community energy systems. By standardizing the functional interface in simulation, the interoperability of the BPS module will be largely enhanced.

5.3. Standard naming convention

The academic literature has revealed the significance of a standard classification system for built environment terms [40]. Classifying building elements in a standard way is essential to progress in organizing building product libraries. By adopting such a standard classification system, the organizational naming convention in AEC/FM industry, then, benefits the KBS by providing consistent terminology. The most popular encoders include OmniClass, MasterFormat, UniFormat, and UniClass. Among them, UniClass was developed and used in a UK context while the other three in North America. Those encoders were developed referring to ISO 12006-2:2015, however, currently none of them has been ISO certified at this stage. Without an ISO standard, the proposed system was limited within a context based efficient use.

5.4. Standard evaluation system

To date, buildings vary from one to another while the money efficiency of operation can hardly be measured [41]. Towards this end, researchers attempted to explore the efficient building performance evaluation methods. With a standardized evaluation process, the results were expected to provide insight into decision-making on supervising

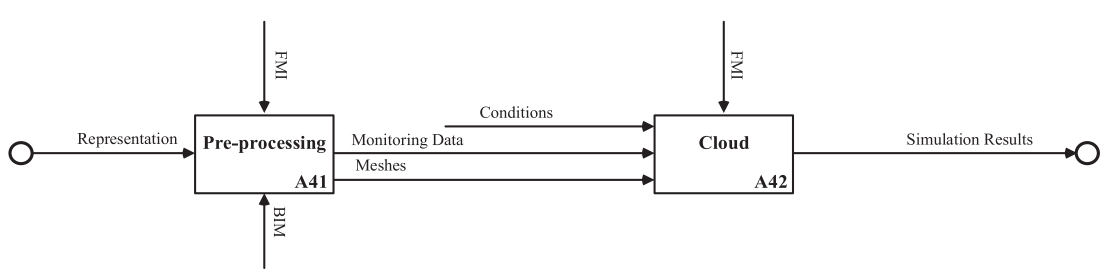

Fig. 16. A4 BPS module (level 1 cloud-based) sub-module division.

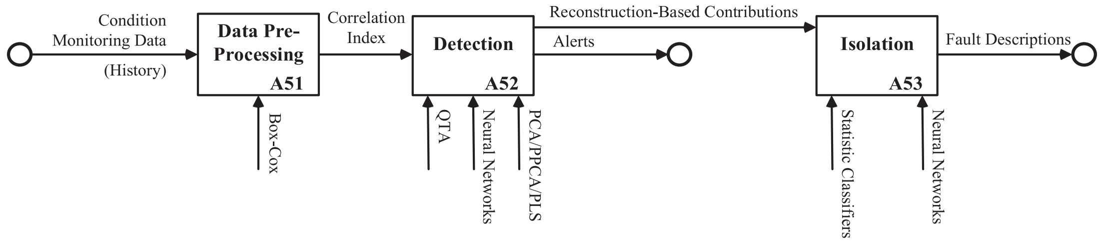

Fig. 17. A5 FDI module (level 1 process history-based) sub-module division.

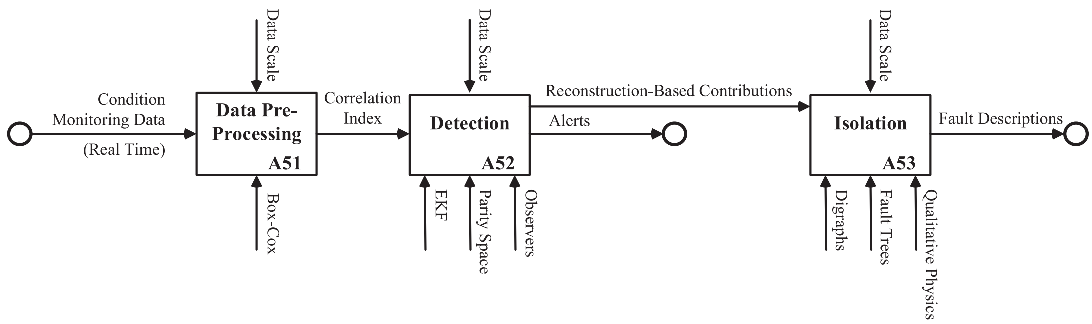

Fig. 18. A5 FDI module (level 2 real-time) sub-module division.

the operation. To this end, several green building standards were developed, such as BREEAM, LEED, CASBEE, Green Star NZ [42]. These standards intended to show the end users how sustainable a building is. With a notice of this, the facility operation was expected to approach a more efficient supervisory. However, standards vary from country to country. Without an agreement, the proposed system was limited within a context based efficient use.

6. Flexibility

As mentioned before, the modules in the proposed system are evolving. That is to say, updating a sub-module with minimum influence on the left parts is a big challenge. To obtain a highly flexible complex system, this study follows the independent axiom:

> "Maintain the independence of the functional requirements (FRs)."
>
> Suh [43]

This axiom was adopted to standardize the modulization (A0: A1–5) of the proposed framework. With such standard modulization, the flexibility of our system to switch out or introduce additional modules has mainly been increased. In this section, a deduction will be conducted to demonstrate the satisfaction of the proposed system for the independent axiom. For verifying the functional independence, Design Structure Matrix (DSM) is selected as examining factors [44]. Once a DSM can be uncoupled into a coupled matrix or a quasi-coupled matrix, the Independence Axiom requirements can be satisfied [45].

Towards obtaining a simulation-based supervisory control while operational faults were detected and diagnosed automatically, the FR_0 has been divided into five FRs (see in Table 1). Centralizing each FR separately, five DPs have been designated. Despite this, interactions with other DPs exist when one DP attempts to deliver the required functions to its corresponding FR. For instance, to meet the FR_5, DP_5 was designed to recognize the operational faults coupled with their information. Wherein, DP_5 needs to process the conditional monitoring data obtained from DP_1. Thus, interactions between FR_5 and DP_1 exist. To illustrate the relationship between FRs and DPs, a matrix diagram has been developed to demonstrate the relationship between FRs and DPs (see Table 3). Given this, the DSM for mapping FRs and DPs has been established as shown in Eq. (1) (X: influence; 0: no influence) (see Table 2).

$$\begin{vmatrix} FR_1 \\ FR_2 \\ FR_3 \\ FR_4 \\ FR_5 \end{vmatrix} = \begin{vmatrix} X & 0 & 0 & 0 & 0 \\ X & X & 0 & 0 & 0 \\ 0 & X & X & 0 & X \\ 0 & X & 0 & X & 0 \\ X & 0 & 0 & 0 & X \end{vmatrix} \begin{vmatrix} DP_1 \\ DP_2 \\ DP_3 \\ DP_4 \\ DP_5 \end{vmatrix} \tag{1}$$

Then, the DSM was decoupled:
First, exchange the FR_3 and FR_4 rows (see Eq. (2));

$$\begin{vmatrix} FR_1 \\ FR_2 \\ FR_4 \\ FR_3 \\ FR_5 \end{vmatrix} = \begin{vmatrix} X & 0 & 0 & 0 & 0 \\ X & X & 0 & 0 & 0 \\ 0 & X & 0 & X & 0 \\ 0 & X & X & 0 & X \\ X & 0 & 0 & 0 & X \end{vmatrix} \begin{vmatrix} DP_1 \\ DP_2 \\ DP_3 \\ DP_4 \\ DP_5 \end{vmatrix} \tag{2}$$

Second, exchange the DP_3 and DP_4 column (see Eq. (3));

$$\begin{vmatrix} FR_1 \\ FR_2 \\ FR_4 \\ FR_3 \\ FR_5 \end{vmatrix} = \begin{vmatrix} X & 0 & 0 & 0 & 0 \\ X & X & 0 & 0 & 0 \\ 0 & X & X & 0 & 0 \\ 0 & X & 0 & X & X \\ X & 0 & 0 & 0 & X \end{vmatrix} \begin{vmatrix} DP_1 \\ DP_2 \\ DP_4 \\ DP_3 \\ DP_5 \end{vmatrix} \tag{3}$$

Third, exchange the DP_4 and DP_5 columns (see Eq. (4)).

$$\begin{vmatrix} FR_1 \\ FR_2 \\ FR_4 \\ FR_3 \\ FR_5 \end{vmatrix} = \begin{vmatrix} X & 0 & 0 & 0 & 0 \\ X & X & 0 & 0 & 0 \\ 0 & X & 0 & 0 & X \\ 0 & X & X & X & 0 \\ X & 0 & X & 0 & 0 \end{vmatrix} \begin{vmatrix} DP_1 \\ DP_2 \\ DP_4 \\ DP_3 \\ DP_5 \end{vmatrix} \tag{4}$$

Last, exchange the FR_4 and FR_5 rows (see Eq. (5)).

$$\begin{vmatrix} FR_1 \\ FR_2 \\ FR_5 \\ FR_3 \\ FR_4 \end{vmatrix} = \begin{vmatrix} X & 0 & 0 & 0 & 0 \\ X & X & 0 & 0 & 0 \\ X & 0 & X & 0 & 0 \\ 0 & X & X & X & 0 \\ 0 & X & 0 & 0 & X \end{vmatrix} \begin{vmatrix} DP_1 \\ DP_2 \\ DP_4 \\ DP_3 \\ DP_5 \end{vmatrix} \tag{5}$$

As a result, Eq. (5) is a quasi-coupled matrix that meets the requirements of the Independent Axiom. Hence, the overall system was functional independent.

Additionally, two pathways were highlighted to achieve the FR_0:

Table 1
The divisions of FRs, DPs, and Cs.

Factors	Contents	Divisions
FR_0	To provide simulation-based supervisory control while automatically detecting and diagnosing operational faults	FR_1: to provide automatic centralized control of building facilities FR_2: to provide a database capable of detailly describing buildings FR_3: to solve new problems based on the solutions of similar past cases FR_4: to simulate the building performance and provide an optimized scheme for building management FR_5: to recognize the operational faults and pinpoint the type of fault and its location
DP_0	ND BIM-IKBMS	DP_1: A1 BAS module DP_2: A2 BDS module DP_3: A3 CBR module DP_4: A4 BPS module DP_5: A5 FDI module
Cs	Interoperability	C_1: protocols C_2: MVDs C_3: encode C_4: FMIs C_5: data scale

6.1. Simulation-based supervisory control (SBSC)

This pathway aims to conduct smart control under the supervision of simulated results. With this in mind, three modules were geared up. First of all, the A1 BAS Module monitored the built environment and sent the data to the A2 BDS Module. Coupled with the 3D representation of the building facilities, such monitoring data was sent to A4 BPS Module for decision-making on operational strategy. After simulation, the results were sent to the end users who were supervising the A1 BAS Module (see Fig. 19).

Within this pathway, the relationships among FRs and DPs were mapped in Table 3.

Given this, the DSM for mapping FRs and DPs has been developed as shown in Eq. (6).

$$\begin{vmatrix} FR_1 \\ FR_2 \\ FR_4 \end{vmatrix} = \begin{vmatrix} X & 0 & 0 \\ X & X & 0 \\ 0 & X & X \end{vmatrix} \begin{vmatrix} DP_1 \\ DP_2 \\ DP_4 \end{vmatrix} \tag{6}$$

As a result, Eq. (6) is a quasi-coupled matrix that meets the requirements of the Independent Axiom. Hence, the SBSC pathway was functional independent.

6.2. Fault-finding supervisory control (FFSC)

This pathway aims to carry on detecting and isolating the operational faults while retrieving solutions from past cases. With this in mind, four modules were equipped. First of all, the A1 BAS Module acquired the facility condition monitoring data and sent the data to the A5 FDI Module. After processed, the fault descriptions were sent to A3 KBS Module. Meanwhile, asset information (identification, location, etc.) was sent to A3 KBS Module from A2 BDS Module. The end users were alerted by fault detected paired with its location while received the suggested solutions from past cases. Besides, the end users can also make a manual query when needed (see Fig. 20).

Within this pathway, the relationships among FRs and DPs were mapped in Table 4. Given this, the DSM for mapping FRs and DPs has been developed as shown in Eq. (7).

$$\begin{vmatrix} FR_1 \\ FR_2 \\ FR_3 \\ FR_5 \end{vmatrix} = \begin{vmatrix} X & 0 & 0 & 0 \\ X & X & 0 & 0 \\ 0 & X & X & X \\ X & 0 & 0 & X \end{vmatrix} \begin{vmatrix} DP_1 \\ DP_2 \\ DP_3 \\ DP_5 \end{vmatrix} \tag{7}$$

To begin with, exchange the DP_3 and DP_5 columns (see Eq. (8)).

$$\begin{vmatrix} FR_1 \\ FR_2 \\ FR_3 \\ FR_5 \end{vmatrix} = \begin{vmatrix} X & 0 & 0 & 0 \\ X & X & 0 & 0 \\ 0 & X & X & X \\ X & 0 & X & 0 \end{vmatrix} \begin{vmatrix} DP_1 \\ DP_2 \\ DP_3 \\ DP_5 \end{vmatrix} \tag{8}$$

Then, exchange the FR_3 and FR_5 columns (see Eq. (9)).

$$\begin{vmatrix} FR_1 \\ FR_2 \\ FR_5 \\ FR_3 \end{vmatrix} = \begin{vmatrix} X & 0 & 0 & 0 \\ X & X & 0 & 0 \\ X & 0 & X & 0 \\ 0 & X & X & X \end{vmatrix} \begin{vmatrix} DP_1 \\ DP_2 \\ DP_3 \\ DP_5 \end{vmatrix} \tag{9}$$

As a result, Eq. (9) is a quasi-coupled matrix that meets the requirements of the Independent Axiom. Hence, the FFSC pathway was functional independent.

This study divided a complex system (A0) into five modules while each module standardized to be functional independence. The results of this research support the idea that by developing under a standard modulization, an updated module can replace its old one with minimum influence on other modules. Therefore, the proposed framework maintains high interoperability to change.

7. Conclusions

This is the second step of the nD BIM-IKBMS research. The significance of nD BIM-IKBMS has been demonstrated in the previous

Table 2
Mapping between FRs and DPs for nD BIM-IKBMS.

FRs	DPs				
	DP_1	DP_2	DP_3	DP_4	DP_5
FR_1	Self-interaction	Independent operation	Independent operation	Independent operation	Independent operation
FR_2	Monitoring data	Self-interaction	Independent operation	Independent operation	Independent operation
FR_3	Independent operation	Asset information	Self-interaction	Independent operation	Fault descriptions
FR_4	Independent operation	Representation	Independent operation	Self-interaction	Independent operation
FR_5	Condition monitoring data	Independent operation	Independent operation	Independent operation	Self-interaction

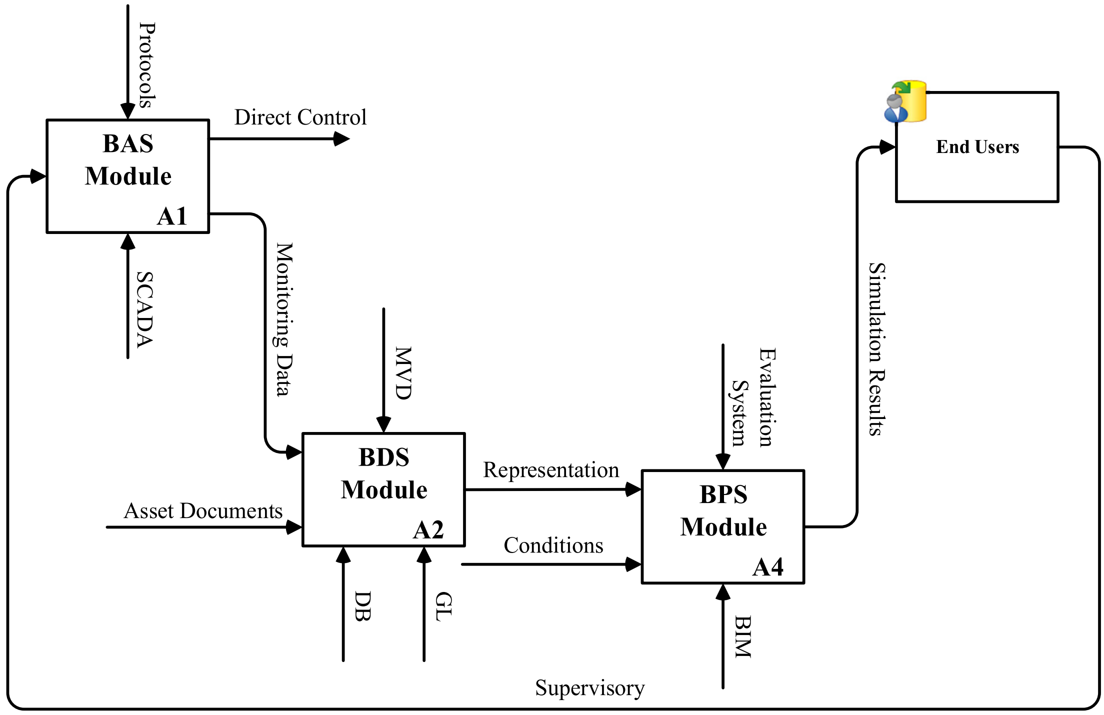

Fig. 19. SBSC pathway modulization.

Table 3
Mapping between FRs and DPs for SBSC.

FRs	DPs		
	DP_1	DP_2	DP_4
FR_1	Self-interaction	Independent operation	Independent operation
FR_2	Monitoring data	Self-interaction	Independent operation
FR_4	Independent operation	Representation	Self-interaction

article. In this research, we have designed a conceptual framework for the nD BIM-IKBMS. Such a framework will be used for developing a software solution in the coming research. Such a solution will be expected to improve the post-construction energy efficiency and maintenance effectiveness. Meanwhile, the proposed framework provides a pre-condition for the organizations which aims at achieving a higher BIM maturity level, especially BIM Level 3 and further. In this article, three findings have been represented:

- To identify the functional requirements for the proposed system to fulfill the expectations, this research used the Axiomatic approach for the nD BIM-IKBMS functional design. The A0-level framework of nD BIM-IKBMS is designed to reduce the post-construction energy consumption by intelligent controls and historic retrievals. Then, the proposed system has been developed into five modules. Each module has been classified into several evolution levels or options. Before applying the proposed framework for a system, a designated combination of those five modules under different levels/options was made based on the developing conditions. Once a module needs to add additional functions, the developer can simply replace the old module with a new one that is developed under the modulization standard. Such standard has designated the interactions with other modules.
- To verify the efficient integration of BIM and KBS to improve the performance BMS, the proposed framework has to meet the requirements of the interoperability. Various communication protocols, data formats, naming conventions, and evaluation systems represent the most significant challenges of interoperating the proposed system. This study suggests that the best way to maintain the interoperability is standardizing the process: to adopt a standard communication protocol instead of a vendor-proprietary protocol; to use the IFC format rather than a software-proprietary format; to follow a standard encoder rather than a company-proprietary naming convention; to refer to a standard evaluation system rather than project-proprietary evaluation.
- To keep the flexibility of the proposed system towards module replacement, the modulization should be standardized based on Independence Axiom. Each module should be functionally independent. To put it into another way, the DSM of the proposed system should be either a coupled matrix or a quasi-coupled matrix.

This system is not limited to energy optimization systems only. It is capable of being extended substantially. Since the system follows a modular platform, this research focused on building energy performance as a case alone, to verify the developed system. It is evident that the additional custom modules, developed on a fit-to-purpose basis, is the future of the proposed nD BIM-IKBMS. Addition of navigation and emergency (structural health monitoring, smoke, gas, and glass break detection, etc.) modules to the system are just two side projects currently being suggested. These will be integrated with Augmented Reality (AR)/Virtual Reality (VR) technology techniques. Real-time analysis of the proposed system's big data concerning all end users plus web-based visualization will be included in the upcoming versions of nD BIM-IKBMS.

Acknowledgments

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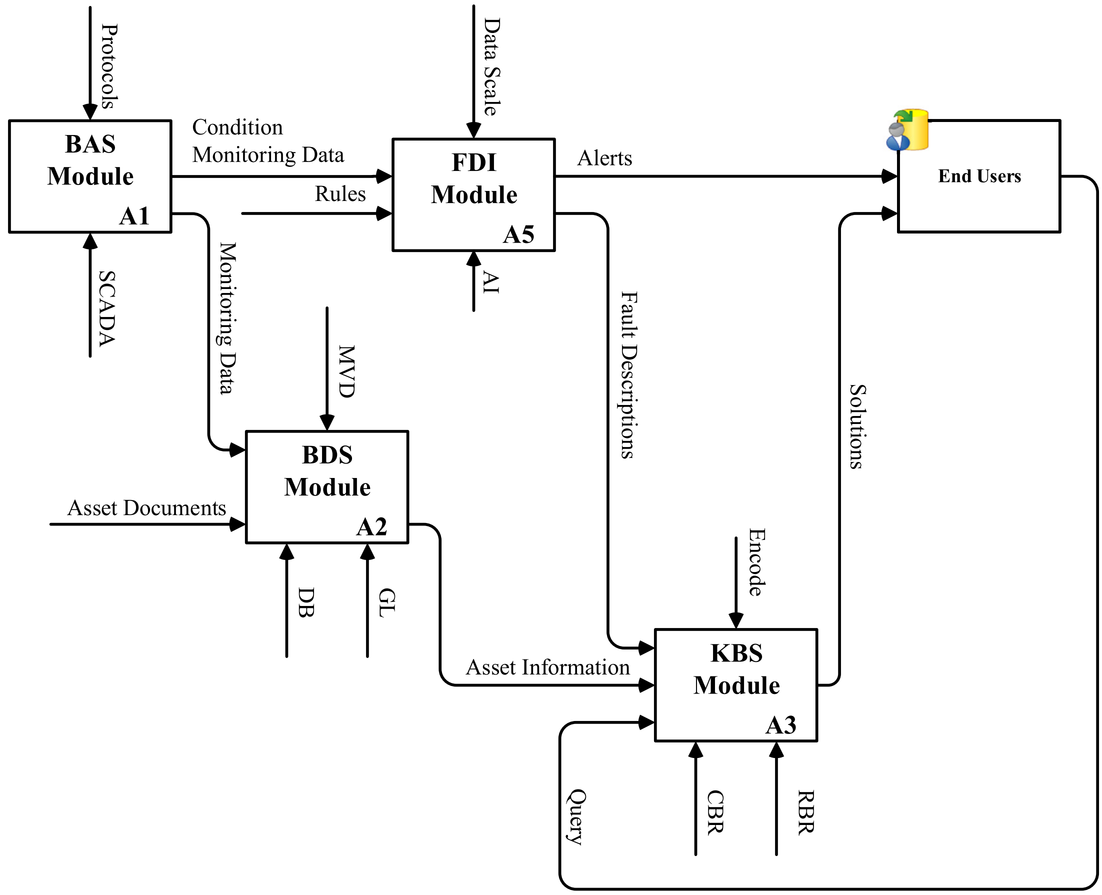

Fig. 20. FFSC pathway modulization.

Table 4
Mapping between FRs and DPs for AFDI.

FRs	DPs			
	DP_1	DP_2	DP_3	DP_5
FR_1	Self-interaction	Independent operation	Independent operation	Independent operation
FR_2	Monitoring data	Self-interaction	Independent operation	Independent operation
FR_3	Independent operation	Asset information	Self-interaction	Fault descriptions
FR_5	Condition monitoring data	Independent operation	Independent operation	Self-interaction

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