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Activity theory-based analysis of BIM implementation in building O & M and first response

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ABSTRACT

The construction industry has worked towards embracing Building Information Model (BIM) innovations for improving the efficiency, accuracy and reliability nowadays. However, the implementation of BIM in building Operations & Maintenance (O & M) is still limited. Previous research only focused on identifying influential factors for the promotion of BIM use in building O & M without considering the systematic manner and the dynamic nature of technology evolution process. This study thus aims to establish an analytical activity system model (ASM) using the activity theory to analyze the BIM use in building O & M in a systematic and dynamic way. The ASMs (traditional and evolutionary) of two different statuses (i.e., without and with BIM-assisted O & M) and the corresponding evolution processes were established based on the critical process models with actors and activities identified in the 1st round interviews with 14 experts. Then, the *contradictions* as the drivers of evolution in the ASM from the traditional one to the evolutionary BIM-assisted O & M have been examined based on the 2nd round interviews involving the 14 experts and 32 questionnaire surveys. An ASM based driver model of evolution for the BIM-assisted O & M is finally constructed. 26 innovation-oriented internal drivers and six demand-oriented external drivers have been identified, and 21 recommended actions, with the context of social, political and technical influences, have been proposed correspondingly to enhance the identified drivers to achieve BIM-assisted O & M. These results provide a map for O & M practitioners, policy makers and researchers to promote the implementation of BIM in O & M, and are beneficial to the delivery of BIM in building O & M.

1. Introduction

The operation and maintenance (O & M) phase is definitely significant from the life-cycle perspective, which covers over 85% of the total costs in ownership and 30–50 years of the total time span [1]. It is also a complex and comprehensive process requiring multi-tasks and multi-participants (e.g., owners, property staff, and workers) involved. The comprehensive information (e.g., historical O & M records, list of reliable specialist professionals and vendors, accurate locations etc.) recorded and exchanged in the O & M process thus should keep the integrity, validity and interoperability to improve the cooperation efficiency and accelerate O & M activities. Previous studies have explored and developed tools and systems with improved information to enhance O & M management, including Computerized Maintenance Management Systems (CMMS), Computer-Aided Facility Management (CAFM) systems, Building Automation Systems (BAS), and Integrated Workplace Management Systems (IWMS) [2]. However, even though different tools have been studied and developed, there is still a lack of an integrated and intelligent platform that could manage and support various activities in building O & M [3]. For instance, although CMMS is a computerized system being able to record daily work orders, track historically records, manage service requests and store maintenance information, it requires great efforts and time for facility management (FM) staff to extract diverse and also scattered O & M information in need, including data within CMMS, specifications, 3D models etc. (ibid). Although several approaches such as Radio Frequency Identification (RFID) have been prompted to aid in extracting O & M data from daily as-is conditions, it is still limited by its information sharing strategies among different stakeholders [4].

Building Information Model (BIM), as a digital representation of a building, has been proposed as an innovative and practical approach to store, visualize and exchange building information in design, construction and O & M phases. It can minimize the information loss in building life cycle and act as a central database in O & M [5]. Furthermore, integrated and comprehensive solutions for O & M can be provided by adapting BIM to improve the interoperability and collaboration among stakeholders in O & M (ibid). For instance, Motawa and Almarshad proposed a Case-Based Reasoning (CBR)-integrated BIM

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Table 1
Previous studies on the factors influencing BIM implementation in building O & M.

Factors	Methodology	Reference
Building information availability and accessibility, stakeholder capability, and O & M process effectiveness	Literature review, expert interview	[64]
Costs, BIM knowledge and attitude of FM staff, education/training costs, collaboration, interoperability, BIM transfer, liability	Questionnaire-based survey	[65]
Roles and responsibilities of key stakeholders, data requirements for BIM model, FM staff's input during building delivery, information exchange between different parties; BIM knowledge and attitude of FM staff	Literature review	[67]
BIM functionalities, informational structure and data exchange, model creation process, responsibility and liability of stakeholders, information interoperability	Literature review	[62]
Organizations' plans and experience in implementing BIM, information exchange mechanism, and varying levels of BIM adoption	Case study	[61]
Inevitable inaccuracy of data input, data exchange and interoperability issue, high cost of BIM	Case study	[63]
Ownership of BIM, liability, risks, and contracts, costs, sociotechnical issues arise from the adoption of new technology, knowledge and expertise required for BIM use	Case study	[66]
BIM implementation requirements for multidisciplinary model sharing, work process within/across organizations to guide the integration of BIM, organizational intends to support BIM	Expert interview, survey	[11]
Conflicting objectives and different constraints, large numbers of strategies in asset management, difficulty in trading off strategies under multiple outcomes	Deterministic optimization method, case study	[12]
Requirement on BIM management, design review, data security and BIM-server set-up implementation	Focus group interview, case study	[13]
Strategic competencies, administrative competencies, operational competencies of building owners	Delphi technique	[14]

system for building maintenance to improve the efficiency of decision making and communication [6]. Shanghai Center in China also applied BIM in O & M, which integrated disparate BIM, CMMS, and BAS systems of a courthouse [7]. Nonetheless, the adoption rate of BIM in O & M is still low in fact nowadays. According to the report from McGraw Hill Construction, only 25% of U.S. public owners and 11% of the private sector indicated that they had set their own formal requirements for BIM [8].

Previous research has identified several influential factors for the promotion of BIM use in the building O & M (as shown in Table 1). For instance, the report from McGraw Hill Construction pointed out that the diffusion of BIM largely pertains to actors' willingness and readiness for conducting O & M activities with computerized ways instead of conventional ways. Although they may realize great value in using BIM during O & M, actors usually lack the IT technical knowledge required to use BIM [8]. Sun [10] also regarded the transition of people's mindset from traditional to new methods of O & M as the key factor to facilitate the BIM use in O & M, where the transition can be achieved through human activity-oriented innovation and training. Parsanezhad and Dimyadi [9] thought the conventional business processes and contracts needed to be updated accordingly. Gerrish et al. [64] identified that there were three kinds of influential criteria for delivering the adoption of BIM in O & M, including the building information availability and accessibility, stakeholder capability, and O & M process effectiveness. Cavka et al. [61] and Volk et al. [62] both figured out that the organizational issues, information and techniques could act as drivers to accelerate the BIM use in building O & M. However, these studies just identified the influential factors for promoting BIM implementation in O & M without considering the systematic manner and the dynamic nature of technology evolution process. In addition, there is also a lack of comprehensive analysis for the use of BIM in building O & M from the perspective of multiple stakeholders involved [11,63,64].

Although a framework has been proposed to help facility owners assess their BIM competency [14], a systematic and dynamic mechanism is still in need for the comprehensive analysis of human activity-related contextual issues of BIM use in O & M for existing buildings in order for the owners to clearly understand their status in BIM implementation and develop implementation plans accordingly. Activity theory is thus used in this study to provide a comprehensive and systematic method for understanding and diagnosing factors and corresponding evolution process that can accelerate the BIM use in building O & M in a consistent and dynamic way. This study aims to establish an analytical activity system model (ASM) using the activity theory to (1) analyze the current practices of building O & M, (2) explore the drivers that may prompt BIM implementation in building O & M, and (3) find out corresponding opportunities with recommendations in enhancing the identified drivers.

2. Activity theory and its applications

The activity theory, also known as cultural historical activity theory (CHAT), provides a broad theoretical framework for describing the structure, development and context of human activity [15]. Initiated by the Russian psychologists Vygotsky and Leont'ev [16,17], the activity theory was originally designed to provide an analytical framework for human-computer interaction (HCI), and further has been widely applied to the design of computer supported cooperative work (CSCW) [18]. However, beyond the design of CSCW, nowadays the activity theory also provides a philosophical and cross-disciplinary analytical framework for different forms of human practices at both individual level and social level to identify and organize causal factors in a more consistent, systematic way [19], including diagnosis of human-related accidents in high-risk industries [20], study of behaviors in problem structuring methods interventions [21], investigation of human choice of tools in innovation diffusion [10].

In the construction industry, the activity theory has also been used as a theoretical basis for analyzing the complexity and interactions of actions in projects, and interpreting the development of tools in activities. Floricel et al. deployed the activity theory to analyze the role of technology in resolving *contradictions* within and between activity systems in project management [22]. Mäki and Kerosuo examined the types of BIM uses and corresponding problems in the construction site management based on the activity theory [23]. In particular, Allen et al. applied the activity theory as a conceptual framework to spotlight information sharing and interoperability issues in emergency response [24], which indicates the possibility of applying the activity theory as a useful analytical tool for modeling and analyzing human activity-related contextual issues of BIM use in building O & M.

According to the original model for describing human behavior, every human activity can be modeled and explained by the triadic relationship between a *subject* and an *object* mediated by *tools* or artifacts. However, these three elements (*subject*, *object*, and *tool*) cannot be pulled apart without violating the core essence of human activity [17]. In order to describe and explain human behaviors in a more consistent and systematic way, three more elements (i.e., *community*, *division of labor* (*DoL*), and *rules*) are incorporated into the original model [25], being called an activity system and represented as an activity triangle shown in Fig. 1. In traditional building O & M, this system can be reorganized with following definitions:

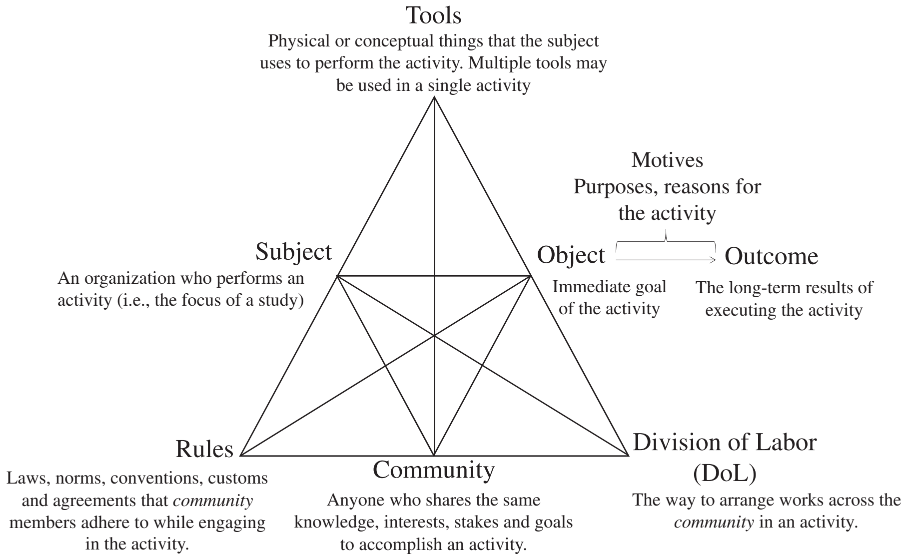

Fig. 1. Elements of activity system model (ASM).

Subject: FM professionals who performs building daily O & M and first response;
Object: A completed system, which can maintain, diagnose, repair and replace building components and FM systems;
Outcome: Meeting the health and safety requirements of users;
Tools: Equipment, information and knowledge that FM professionals can use to perform the building daily O & M and first response;
Community: Key stakeholders who shares the knowledge, interests, and stakes to accomplish the building O & M;
Rules: Laws, norms, O & M manuals, agreements, general specification and guidance that key stakeholders adhere to while engaging in building daily O & M and first response. Relations between FM professionals (*Subject*) and key stakeholders (*Community*) are mediated by *Rules*;
Division of Labor (*DoL*): The ways to arrange works related to daily O & M and first response among key stakeholders in the *Community*. Relations between the *Object* and key stakeholders in the *Community* are mediated by *DoL*;

There are five basic principles of the activity theory for understanding human activities: (1) object-orientedness; (2) hierarchical structure of activity; (3) internalization and externalization; (4) tool mediation; and (5) historical development [25]. Based on these theoretical bases, activities can be further analyzed through a set of key terms, namely *interaction*, *mediation*, *disturbance*, *contradiction* and *evolution* [20,26].

Interaction: *Subject*, *object* and *community* are three main interacting elements. Therefore, the three main types of interactions are: *subject-object*, *subject-community*, and *community-object*.

Mediation: *Tools*, *rules*, and *DoL* are three mediating elements. Three primary mediating relationships are: a *tool* mediates the interaction between a *subject* and the activity *object* (the subject achieves the object by using a tool); *rules* mediate interactions between the *subject* and the *community*; and *DoL* mediates interactions between the *community* and the *object* of the activity. Secondary mediating relationships may also exist in the model. For example, *rules* may mediate between the *community* and the *object*, or between the *subject* and the *object*.
Disturbance: Human activities are reformed and reshaped through historical development; the activity system becomes unstable accordingly and makes adjustments in order to get a new status. *Disturbance* and *contradiction* are used to describe and analyze in-depth problems related to human activities [27].
Disturbance describes surface problems, which is a significant index to figure out hidden causes. Hence, it is necessary to identify disturbances in the comprehensive contextual background from multiple perspectives before *contradiction*.
Contradiction: This term indicates the historically accumulated structural tensions within different elements of an activity system, between different elements, between different activities or different development phases of the same activity system [28], and reflects in-depth factors resulting in the adjustment of ASM when encountering changes. There are four types of *contradictions*, namely primary, secondary, tertiary and quaternary. Each of them indicates the misfit within an element, the misfit between two elements, the misfit between different development phases of an activity, and the misfit between different concurrent activities [20].
Evolution: *Contradictions* often exist in different status within human activities. Hence, *evolution* may be triggered due to these *contradictions*. The adoption of new elements from outside of the system (e.g., new technology) aggravates *contradictions* within an activity or among different activities, which emerges as *disturbances* and also as attempts to evolve a new status in this activity system [23]. *Evolution* occurs to relieve *contradictions* within and between elements and in previous status of an activity [26].

Compared to previous methods developed to support similar cognitive analysis processes, such as Human Performance Enhancement System (HPES) [29], Human Performance Investigation Process (HPIP) [30] and Human Factors Investigation Tool (HFIT) [31], the activity theory rejects the isolated human being as an adequate unit of analysis, but introduces 'activity' as the basic unit of human behavior analysis [15]. It encourages discussions by diverse groups of stakeholders, and can be useful in situations where it is necessary to explore the diverse communities and social contexts of a system. The activity theory is thus adopted in this study to provide a meta-theory that describes and explains O & M activities in a more consistent, systematic and theoretical grounded way, and also to identify drivers and opportunities of BIM implementation in building O & M.

3. Research methodology

This research consists of four stages (Fig. 2). The first stage is to identify process models for daily O & M, first response and mandatory building safety inspection scheme under two different statuses according to the 1st round interview and data collected through literature review: (1) status 1: traditional building O & M, and (2) status 2: BIM-

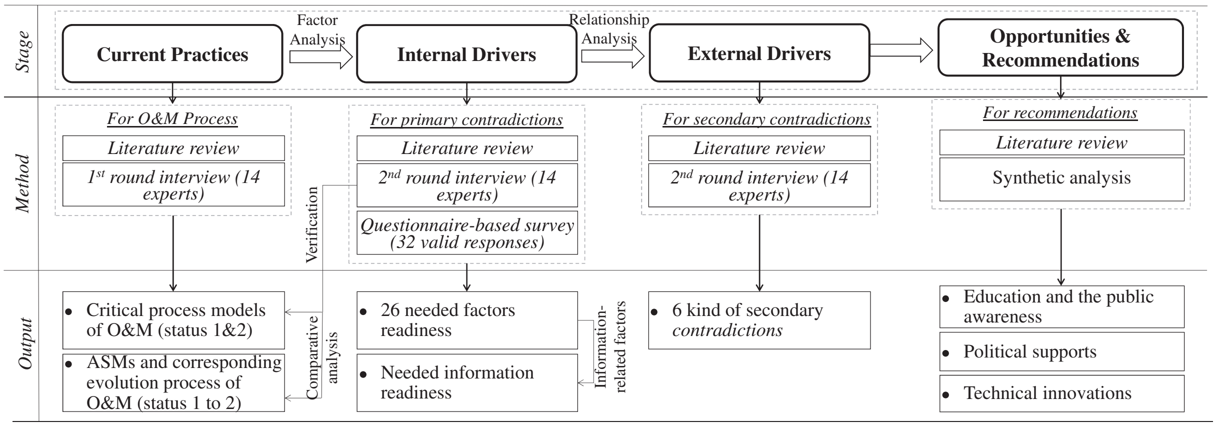

Fig. 2. Research methodology based on ASM.

assisted building O & M. Based on these two process models, actors and activities involved in each separated process are also examined, with which ASMs of daily O & M and first response for status 1 and 2 (traditional and evolutionary) can be further established, respectively.

The second stage is to conduct factor analysis based on the examined current practices for identifying primary *contradictions* as internal drivers within the elements to implement BIM in O & M. After the modification and verification based on 2nd round interview, a questionnaire survey was conducted to determine readiness of factors and information for the implementation of BIM-assisted O & M as internal drivers. Similar to the technological readiness level (TRL), the readiness of factors in this paper is the necessity of factors for accelerating the evolution from the traditional O & M process to the BIM-assisted O & M process. This collective consideration of six perspectives (i.e., *subject*, *tools*, *object*, *rules*, *community*, and *DoL*) is helpful to understand the dilemma of BIM implementation in O & M within the comprehensive context of human activity and management.

Then, in the third stage, relationship analysis was conducted based on literature review and the 2nd round interview, which aimed to examine and analyze secondary *contradictions* as external drivers derived from interactions between ASM elements.

Lastly, based on the results of the previous analyses, opportunities and recommendations have been proposed to accelerate BIM implementation in O & M. This synthetic analysis was conducted from three aspects, namely social, political and technical, to enhance the identified drivers triggering the transition from traditional O & M process to the BIM-assisted O & M process.

3.1. Semi-structured interviews

In order to identify and verify actors, activities in the O & M process, and drivers of BIM implementation in O & M, two rounds of semi-structured interviews were conducted. The interviewees include academic researchers in BIM areas, BIM designers and consultants, FM professionals, industrial association members, and government bureau directors, representing different roles in the BIM-assisted O & M process. Each round of the interviews includes 14 face-to-face interviews, and the details of interviewees are summarized in Table 2.

The 1st round interview was conducted to identify critical activities and corresponding actors in the traditional O & M process without BIM and the evolutionary O & M process with BIM. Each interview lasted approximately 30 min, and the interview script mainly included:

- Interviewee's background.
- Critical O & M activities and their sequences, and corresponding actors to establish the two O & M process models (with BIM and without BIM).

Table 2
Summary of the interview respondents (1st round and 2nd round).

No.	Role	Years of experience in O & M	Years of experience in BIM
1	Assistant professor	11	5
2	Visiting research scientist	3	0.5
3	Engineer/manager	13	2
4	Chief technology officer	5	2
5	Visiting professor	25	7
6	Managing director	10	10
7	Development manager	10	5
8	Project director/quantity surveyor	26	6
9	Information technology manager	10	3
10	Senior engineer	10	5
11	Engineer	3.5	2
12	Manager - council service (BIM)	20	10
13	Executive director	10	1
14	Project director	20	6

In the 2nd round interview, the 14 experts who had participated in the 1st round interview were invited again to verify the O & M process models and a corresponding ASM evolution process, and also to initially identify drivers of BIM implementation in O & M. Each interview approximately lasted 1 h, and the interview script mainly included:

- Verification of the constructed process models, ASMs and corresponding evolution process.
- Possible internal drivers of evolution from the traditional O & M without BIM to the BIM-assisted O & M: initial modification and verification of the readiness of factors; initial modification and verification of the readiness of information for the readiness of information-related factors.
- Possible external drivers of evolution from the traditional O & M without BIM to the BIM-assisted O & M: tensions embodied between ASM elements in the traditional O & M process with changes of *tools*.

3.2. Questionnaire survey

In order to explore internal drivers of BIM implementation in O & M in detail, namely the primary *contradictions*, online questionnaire survey was conducted via a survey application. A wide range of professionals (Table 3) who have rich experience and knowledge on building O & M and BIM were invited to collect data of their understanding on the developed ASM evolution process. In this survey, the primary *contradictions*, represented by the readiness of key factors and further explained by the readiness of key information, were identified

Table 3
Summary of the valid survey respondents.

Parameter	Value	Frequency	Percentage (%)
Year of experience	Less than 2 years	3	9
	2–4 years	14	44
	5–7 years	13	41
	More than 8 years	2	6
Profiles of respondent organizations	University and professional bodies	4	12
	Industrial institutions	2	6
	Government departments	2	6
	Manufacturers and suppliers	3	9
	Contractors	4	13
	Estate and facility managers	4	13
	Engineers	5	16
	Architects	4	13
	Developer and clients	4	13
Total	–	32	100

using a five-point Likert scale where 1 represents *Not important* and 5 represents *Very important*.

The questionnaire was sent out to the total number of 150 experts. 39 responses were collected after two weeks, and the response rate was 26%. Among these responses, seven responses were incomplete or invalid, and thus were omitted. The 32 valid responses were analyzed.

4. Daily O & M and first response for existing buildings under two statuses

The process models under two different statuses (i.e., with BIM and without BIM) have been established based on literature review [6,32], and expert interviews.

4.1. Status 1 - traditional O & M process without BIM

As shown in Fig. 3, the traditional O & M process (status 1 in the ASM) consists of three different sub-processes in response to three different O & M use-case scenarios: a) daily O & M, b) emergency O & M, and c) statutory inspection.

In the daily O & M process, users first submit O & M requests (a_{11}) to the estates office, where the general facility manager then acquires the defect information (e.g., maintenance/operation history and records) and locations (a_{21}), and checks the preliminary status of defects (a_{22}). Next, based on the preliminary information and results from the check, they arrange the branch manager to check defect statuses (a_{23}). With the defect information and locations obtained (a_{24}), the branch manager drafts work plans of daily O & M (a_{31}) and submits the plans to the general facility manager for permission (a_{32}, a_{33}). According to the O & M requirements and plans, the general facility manager needs to select required contractors based on the level of defect status (a_{41}). After the site verification, the selected contractors acquire the corresponding defect information from the branch manager (a_{51}), and then establish a maintenance plan and a cost plan based on the contractors' requests (a_{61}). They wait for feedback and approval from the estates office (a_{62}, a_{63}, a_{64}, a_{65}). Under the supervision of the branch manager (a_{71}), the contractors perform the maintenance work and check status before and after the maintenance work (a_{72}). Having finished the company-contracted maintenance work, the contractors then submit the maintenance results and a payment request to the branch manager (a_{81}) who makes an assessment of these results and the payment request (a_{82}), and reports the certified results to the general facility manager (a_{83}). The general facility manager confirms the results of the maintenance work on site, approves the payment (a_{84}, a_{85}), and sends the notification of maintenance results to the users/owners (a_{86}). Finally, with the confirmation of maintenance results from the users/owners (a_{87}), the archive manager and/or the information system manager updates archives and historical records in the facility management archives and database (a_{88}).

In the emergency O & M process, different from the daily O & M process, the general facility manager is the pivot of O & M activities. After efficiently evaluating the emergency warning received (b_{11}) and defect status encountered (b_{21}), the general facility manager needs to organize an emergency meeting with relevant staff members from all departments (including the branch manager, the information manager, the archive manager and others) immediately (b_{31}). In this meeting, an emergency O & M work plan is established and facility management contractors are selected. Similar to the sub-process (a), the selected contractors perform maintenance work (b_{44}) with defect information obtained (b_{41}) and schedule approved (b_{42}, b_{43}). After the maintenance work, the general facility manager then confirms the results of the emergence O & M and the payment request (b_{31}, b_{52}), and sends the notification of emergency O & M results to the users/owners (b_{53}). Finally, the archive manager and the information system manager update relevant information in facility management archives and database (b_{54}).

In order to ensure the healthy performance and safety of existing buildings, statutory inspection is necessary to be conducted by the building authority (BA), including the mandatory inspection and preventive maintenance (c_{21}, c_{22}) in appropriate intervals.

4.2. Status 2 – BIM-assisted O & M process

As shown in Fig. 4, the BIM-assisted O & M process (status 2 in the ASM) also consists of three different sub-processes in response to the three different use-case scenarios: a) daily O & M, b) emergency O & M, and c) statutory inspection. Unlike the complicated work process without the use of BIM in status 1, BIM-assisted O & M means querying key information efficiently, transferring information timely and accurately, and updating data conveniently through integrating the O & M system and BIM. The use of BIM in O & M provides a comprehensive platform for the estates office, linking the O & M professionals and building information. Required information is invoked through BIM, and BIM/IT engineers need to be employed to assist the information system manager. In that way, all repetitive works, including task arrangement, scheduling, information sharing and renewal, can be simplified and accomplished efficiently via this BIM-assisted O & M system to save the human labor and time.

For instance, in the traditional daily O & M (Fig. 3), the general facility manager and the branch manager need to request the defect information from the information system manager and the archive manager separately and repeatedly (a_{21}, a_{24}). However, with the help of BIM, the estates office can access to the needed information directly and arrange the tasks conveniently, eliminating the redundant steps a_{21} and a_{24}. Similar improvement can also be made for the approval of maintenance plan and cost estimation, having only three steps (i.e., a_{61}: *establish*, a_{62}: *reporting*, and a_{63}: *approving*), rather than five steps in the traditional process.

4.3. Comparative analysis between the two O & M processes

Compared to the BIM-assisted O & M process, the traditional O & M process shows three main defects, namely scattered information, limited communication channels and not properly documented professional knowledge from previous experience.

The duplication of activities frequently occurs in the traditional O & M (Table 4). For instance, since field workers often visit the archives room or the site multiple times to acquire information (e.g., historical records, locations and corresponding contractors' information). There are 3 repeated information acquisition activities. The process of checking and verifying this information (e.g., a_{21} and a_{24} in

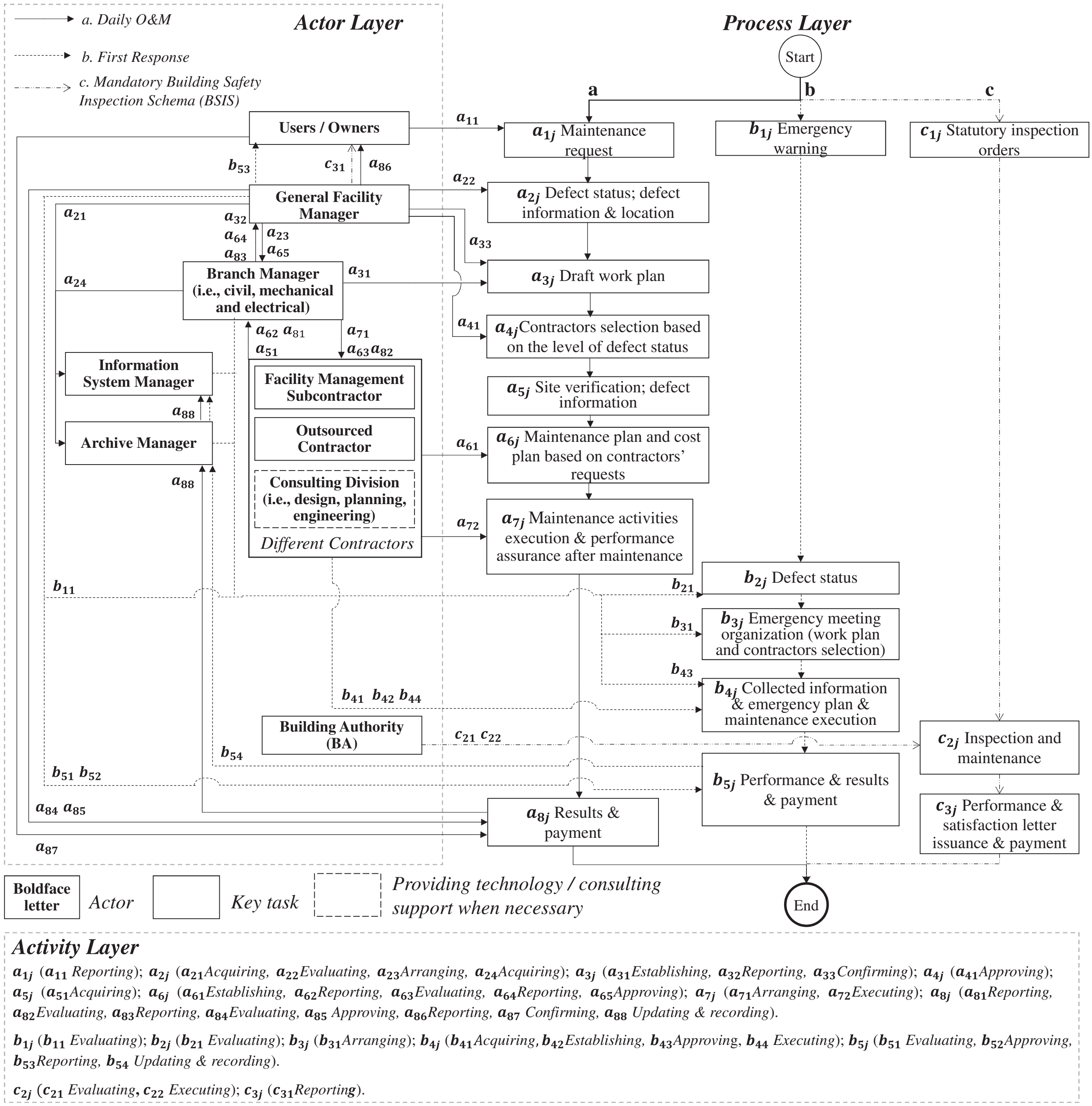

Fig. 3. Status 1: traditional building O & M process.

Fig. 3) is complicated and time-consuming. In addition, according to the interview, in the traditional O & M (Fig. 3), majority of historical records and facility data are usually saved in the Excel spreadsheet file format or even hard-copy format; most floor plans or updated drawings are still stored as original hardcopies or partially CAD files. Even though some maintenance records are managed in a facility information system (e.g., CMMS), it requires a significant amount of time to search, verify and update the corresponding facility information from massive and scattered files before and after (daily & emergency) maintenance, which also might cause errors and deviations.

Besides the scattered information, limited communication channels are the key problem among all facility management staff members. The general facility manager usually acts as a central coordinator and communicates with different parties (e.g., selected contractors or site workers) in status 1. Meetings are seldom organized under daily O & M, and hence, communication channels are limited and knowledge can only be learned within the decision-making team. This is also one of the main reasons for information and experience loss [6].

These problems of the traditional O & M process indicate that there is a need for an intelligent and comprehensive platform to integrate and effectively search O & M information, network all actors, and manage various activities. In that way, with the consideration for convenience of searching, verifying, updating, and managing facility information through a BIM-assisted system, these problems can thus be addressed.

As described in status 2 (Fig. 4), with the help of a BIM-assisted O & M system, this improved O & M process presents a clear

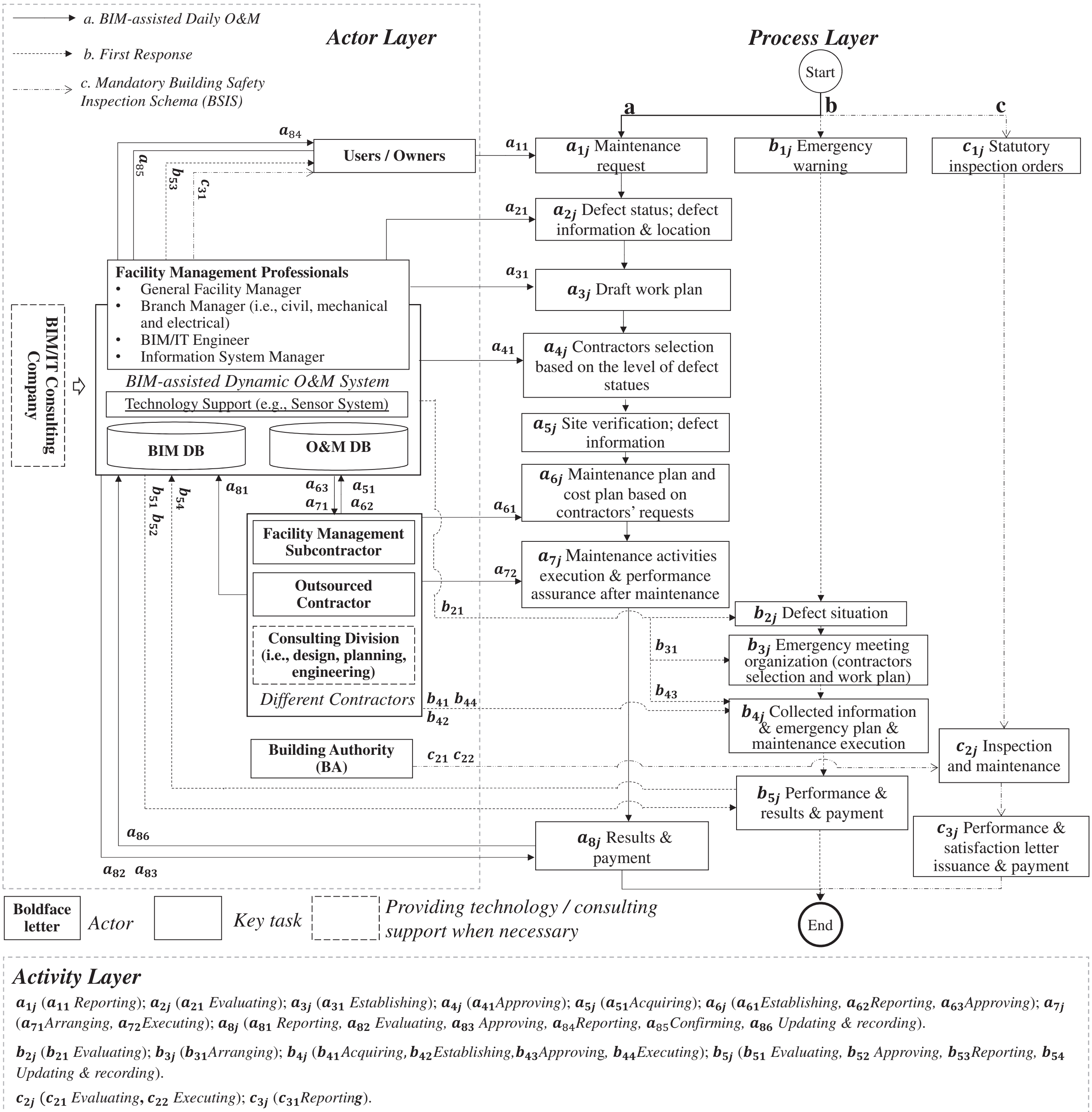

Fig. 4. Status 2: BIM-assisted building O & M process.

management pattern with minimum repetitive activities (Table 4), definitely improving work efficiency and saving time. The BIM-assisted O & M system effectively assists the general facility manager in this advanced process (status 2) in working as a central coordinator and communicating with different parties (e.g., a_{62} and a_{63}), which however can provide adequate and accurate facility information for facility staff in a short time. Furthermore, it is possible to share the information and knowledge based on the same platform conveniently (e.g., a_{86} and b_{54}).

5. Activity system model of O & M for existing buildings

In order to effectively explain how to facilitate the evolution from the traditional O & M process (status 1) to the BIM-assisted O & M process (status 2), the activity theory is applied in this study. In particular, this study focuses on contextualizing and establishing the ASMs (traditional and evolutionary) for daily O & M and first response under different statuses (Fig. 5), identifying the drivers to promote the BIM implementation in O & M and perceived recommendations.

As shown in Fig. 5, in the ASM of status 1, 2D drawings and pieces of traditional O & M equipment are adopted as *tools*, used by *subject*, to achieve the *object* (i.e., building maintenance). The *communities* (e.g., users/owners, contractors, consultants) are involved with different *DoLs*. As mentioned earlier, in the ASM of status 1, executing O & M work is laborious and inefficient due to the scattered information, limited communication channels and undocumented professionals'

Table 4
Summary and comparative analysis of the efficiency of two statuses.

Activity	Actor	Repetitive times	Corresponding sub-tasks	Actor	Repetitive times	Corresponding sub-tasks
Status 1: *Traditional O & M process* (Fig. 3)				*Status* 2: *BIM-assisted O & M process* (Fig. 4)		
Daily operation and maintenance						
Reporting	1; 3; 4; 4; 4; 3; 2	7	$a_{11};a_{34};a_{62};a_{64};a_{81};a_{83};a_{86}$	1; 4; 4; 2	4	$a_{11};a_{62};a_{81};a_{84}$
Confirming	2; 1	2	$a_{35};a_{87}$	2 & 3; 1	4	$a_{31};a_{85}$
Acquiring	2; 2; 4	3	$a_{31};a_{32};a_{51}$	4	1	a_{51}
Evaluating	2; 3; 3; 4; 2	5	$a_{21};a_{33};a_{63};a_{82};a_{84}$	2; 2 & 3	2	$a_{21};a_{82}$
Approving	2; 2; 2	3	$a_{41};a_{65};a_{85}$	2; 2	2	$a_{41};a_{83}$
Establishing	4	1	a_{61}	4	1	a_{61}
Executing	4	1	a_{72}	4	1	a_{71}
Arranging	2; 3	2	$a_{22};a_{71}$	2 & 3	1	a_{63}
Updating & recording	5; 5	2	$a_{88};a_{88}$	6	1	a_{86}
First response						
Evaluating	2; 2 & 3 & 5; 2	3	$b_{11};b_{21};b_{51}$	2 & 3 & 6; 2	2	$b_{21};b_{51}$
Reporting	2	1	b_{53}	2	1	b_{53}
Approving	2 & 3 & 5; 2	2	$b_{43};b_{52}$	2 & 3 & 6; 2	2	$b_{43};b_{52}$
Acquiring	4	1	b_{41}	4	1	b_{41}
Executing	4	1	b_{44}	4	1	b_{44}
Establishing	4	1	b_{42}	4	1	b_{42}
Arranging	2	1	b_{31}	2	1	b_{31}

Note 1: serial numbers of actors: 1 = user/owner; 2 = general facility manager; 3 = branch manager; 4 = selected contractor; 5 = archive and information system manager; 6 = BIM/IT engineer & the information system manager.

experience. With the appearance of new tool (i.e., BIM), the ASM becomes unstable when an element or interaction in the ASM changes, and accordingly makes adjustment in order to return to the stable state, based on the fifth principle (historical development) and the definition of the activity theory [20]. In that way, all the elements in the ASM need to be reformed and reshaped through evolution.

Following the changes of *tools* (from 2D drawings or manual inspection/diagnosis to the BIM-assisted system) and the *object* (from traditional O & M to BIM-assisted O & M), there are inconsistences in the *subject* element of the ASM of status 1. Considering that *tools* are a mediator between *subject* and *object*, there is no connection between the *subject* (i.e., the information system manager and the archive manager) and the new *object*. The following changes would occur in the ASM. For instance, there are some missing *subject* items that should be familiar with the new *tools*, and the BIM/IT engineer should be added to this ASM, forming the newly stable triadic relationship among three elements (*subject*, *object*, and *tools*).

In addition, the interaction between *subject* and *community* (or *object* and *community*) mediated by *tools* helps to identify the missing *community* items in the ASM of status 2. No *community* item that existed in

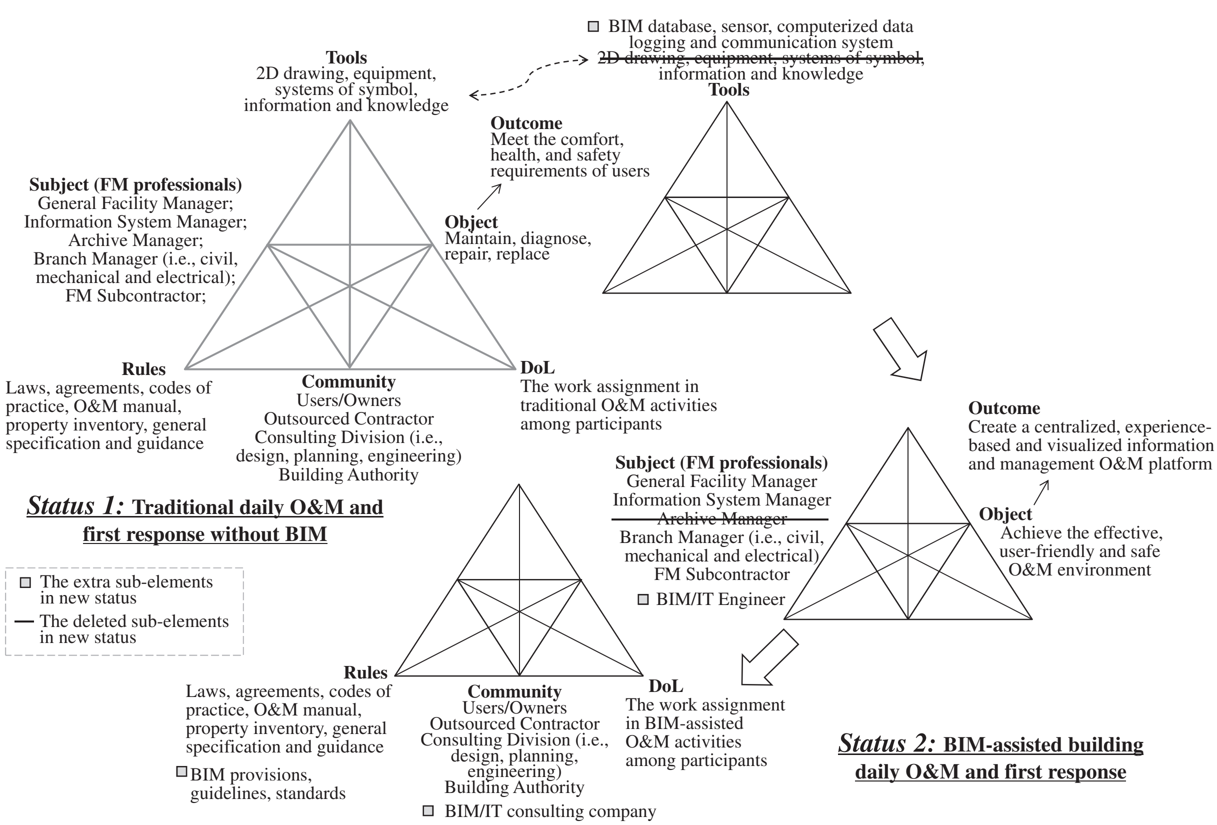

Fig. 5. Structure of ASM and its evolution.

the ASM of status 1 can involve the *subject* (BIM/IT engineer). The asymmetry of this interaction identifies calls for a new *community* item (BIM/IT consulting company) to be added.

Similarly, as the secondary mediating element for interaction between *rules* and *DoL*, *tools* lead to corresponding changes of *rules* and *DoL* to keep the stability of the ASM. Items related to the use of the BIM-assisted system (*tools*) are missing in *rules* and *DoL*. New *rule* items (e.g., BIM provisions, guidelines, and standards) and *DoL* items (e.g., BIM-related work assignment) are thus added into the ASM of status 2.

With the six elements updated, it is revealed that how the purpose of the use of *tools* changes along with changes in actual *objects* and in ways of using *tools* [20], reforming the ASM of status 1 towards the ASM of status 2.

6. Contradictions as the drivers of evolution in the ASM for BIM applications in building O & M

Although the critical evolution process of ASMs for BIM implementation in building O & M has been examined based on the activity theory, it is still ambiguous for majority of FM professionals (*subject*) to understand how to facilitate and realize this evolution via practical steps. The drivers tailored to the O & M process for the shift to BIM-assisted O & M thus should be identified, providing a feasible and realistic approach to accelerating this evolution.

Contradictions within and between key elements (primary and secondary) reveal the inconsistencies and asymmetries inside and between six elements when encountering changes. The tension in the traditional ASM caused by *contradictions* after the changes of *tools* and *object* can drive the evolution of an activity (daily O & M and first response) [26].

6.1. Primary contradictions as the internal drivers of evolution within elements

Primary *contradiction* specifically indicates the misfit within an element of an O & M activity in this study. It can be regarded as the tension between the best possible states of an element and what may be actually implemented or employed within budgeted time and resources [20], and this performance gap can be further filled by the adjustment of corresponding elements derived from the tension. In that way, the primary *contradictions* can act as the drivers to make specific elements adaptive to the changes and return to the stable states again.

6.1.1. Readiness of factors

In this study, the primary *contradictions* are represented by the readiness of the factors needed for each element in ASM, which comprehensively demonstrates the embedded tensions of six elements separately. In order to identify the readiness of these factors and corresponding information, extensive literature review was first conducted. Then 2nd round interview was conducted to fine-tune and verify these initially identified factors and information. Finally, as explained earlier, the questionnaire survey was conducted to determine the factors and corresponding information.

As shown in Table 5, 28 factors have been initially identified via literature review and interviews, representing the primary *contradictions* initially identified in five elements, namely *subject*, *tools*, *rules*, *community*, and *DoL*. After the questionnaire survey, 26 out of them have been determined as the final set. The two factors (i.e., Streamlined labor (F17) and Improved work environment (F19)) are not selected because the survey results show that their importance degrees are “less important” or “neutral”.

For *subject*, the primary *contradictions* mainly result from the collisions between the old *subject* and the expected *subject*. The expected *subject* demonstrates innovative attempts to change the traditional O & M activities from the following three aspects: data management (F1, F4), decision making capacity (F2, F3, and F6), and professional experience (F5, F7). For instance, the desire of new *subjects* with rich experience and comprehensive aptitude towards building O & M (F5) and BIM (F7) drives FM professionals to address the O & M activities from the comprehensive perspective, and enhance their understanding and use of BIM, which also facilitates the appearance of BIM/IT engineers as the newly added *subject* in the ASM of advanced O & M, as shown in Fig. 5.

For *tools*, multiple *tools* are needed by FM professionals (*subject*) to perform preventive, corrective, and predictive maintenance of the targeted building. The primary *contradictions* are mainly produced in the transformation from old *tools* to the advanced BIM-assisted O & M system acted as new *tools* in the evolutionary ASM (Fig. 5). As the requirements for *tools* with the expected performance, the convenience and quality of building information collection and updating (F8, F11, F12, and F27, F28), the ease of use (F9, F26), the specialization of information needs in different phases (F10), and the integrity of stored data (F13), accelerate the regeneration of *tools* in tandem. In that way, sensors system (e.g., ad-hoc temperature, acoustic vibration sensors and barcodes tag), information collecting techniques (e.g., photogrammetry and videogrammetry), and BIM-assisted information systems (e.g., knowledge-based BIM system) can be gradually adopted in the BIM-assisted O & M process.

For *DoL*, primary *contradictions* mainly result from the hysteresis of current cooperation mechanisms responding to the appearance of new *tools* and corresponding adjustments. The existing ambiguous risk allocation plan is insufficient to identify the specific responsibility of each work department, and more appropriate risk allocation systems (F14) should be established. The delivery stage of a project often involves the information loss and mistakes, and the needs for effective task delivering ways (F15) and communication among different work divisions (F16) also promote the progress of O & M work assignment using the BIM-assisted system.

For *community*, only one factor has been determined, which is the BIM consultants' familiarity with O & M procedures (F18). It reveals the variation in professional knowledge between the BIM professional and the FM professional, and thus drives the BIM/IT consulting companies being familiar with both BIM and FM to participate the evolutionary O & M process, as shown in Fig. 5.

For *rules*, regulations and alliance-based contractual agreements are pre-requisites to achieve the successful BIM implementation in O & M. The deficiency of effective supports from *rules* definitely appeals to the initiation of new quality standards (F20, F22), comprehensive BIM standards (F21, F23), and BIM guidance (F24, F25) [5,13].

With the adoption of new *tools*, all five elements except *object* are involved in the evolution of the ASM. The *contradictions* acting as sources of change and development eliminate the out-of-date roles in the traditional ASM (e.g., information system manager, branch manager, and 2D drawings), but also inspire the following appearance of new *subject* (e.g., BIM/IT engineer), new *DoL* (e.g., task delivering ways), new *community* (e.g., BIM/IT consulting companies), and new *rules* (e.g., BIM standards for O & M), as shown in Fig. 5.

6.1.2. Readiness of information for information-related factors

An evolutionary ASM is generated by the changes of elements where BIM plays a significant role in triggering and governing this evolution process (Fig. 5). As a digital representation for buildings, BIM requires the input of sufficient and accurate information about buildings and facilities. The readiness of the 26 factors discussed earlier can thus be further divided into two categories, namely information-related factors focusing on the characteristics of information and non-information factors focusing on the transformation of activities.

As shown in Table 6, most of information-related factors have been further explained by detailed information collected from the 2nd round interview and the questionnaire survey, except F5, F7, F23, and F25. The sets of the detailed information are used to embody the information-related factors in the two categories (i.e., geometry information and non-geometry information [35]), which consequently improves the

Table 5
Survey results on the importance degree of readiness of factors (1: least important, 5: very important, $t_c(31, 0.05) = 2.04$).

Element	Reference	Factors	Mean	SD	t_0
Subject	[3]	F1. Data storage and exchange mechanisms among O & M departments	3.81	0.69	6.61*
	[14]	F2. Ability to assess uncertainties, risks and failures	3.66	0.83	4.51*
		F3. Organizational business process maps	3.34	0.83	2.32*
	Interview	F4. The manner of accessing to data/information/knowledge for FM professionals	4.03	0.86	6.77*
		F5. Professionals' experience and comprehensive understanding towards buildings O & M	3.88	0.71	7.04*
		F6. Decision making support patterns in O & M management	3.63	0.71	5.04*
		F7. BIM experience and aptitude of FM professionals (e.g. understanding of relational databases)	3.66	0.79	4.74*
Tools	[33]	F8. Convenient data updating methods on the basis of as-is conditions for information collecting techniques (e.g., camera)	3.94	0.95	5.61*
		F9. Ease of removal and replacement for sensors system	3.44	0.95	2.62*
	[11]	F10. Specific data provision in project delivery	3.81	0.93	4.92*
	Interview	F11. Advanced facility information collection methods (e.g., RFID)	4.06	0.84	7.14*
		F12. Advanced faults detection methods for sensors system	3.38	0.71	3.04*
		F13. Capacity to keep the integrity of historical O & M records for BIM-assisted information system	3.38	0.87	2.47*
DoL	[11]	F14. Risk allocation in O & M	3.63	0.83	4.28*
	[3]	F15. The appropriate handover patterns from construction phase to O & M phase	3.88	0.83	5.98*
	Interview	F16. Effective communication among different stakeholders in O & M (e.g. designer and facility manager)	3.81	0.78	5.87*
		F17. Streamlined labor	2.97	0.78	− 0.22
Community	Interview	F18. BIM consultants' familiarity with O & M procedures	3.72	0.77	5.28*
		F19. Improved work environment	3.03	0.65	0.26
Rules	[14]	F20. Deficiency of BIM-assisted quality standards for building performance in O & M phrase	3.56	0.67	4.74*
		F21. Deficiency of formal BIM standards and protocols in O & M	3.66	0.90	4.14*
	Interview	F22. Deficiency of BIM-assisted continuous quality assurance mechanism	3.81	0.82	5.58*
		F23. Deficiency of interoperability and automated electronic data delivery among multiple data resources (e.g., data transfer standard)	3.81	0.86	5.33*
		F24. Deficiency of BIM implementation guide in O & M	3.59	0.84	3.99*
		F25. Deficiency of exact requirements defining the level of details (LoDs) at the beginning	3.50	0.92	3.09*
Additional factors (first response)					
Tools	[34]	F26. Convenient access to building and facility information under emergency	4.22	0.66	10.47*
		F27. High quality of data collection in first response	4.25	0.72	9.84*
	Interview	F28. Liability of sensor and technique to capture instant phenomenon	3.97	0.74	7.42*

Note 1: The *t*-test rule of this survey sets out that the indicators with value larger than 3 were considered to be critical. After the t-test of survey results, the null hypothesis (H_0) can be rejected and the alternative hypothesis (H_1) can be accepted with the observed t-value (t_0) larger than the critical t-value (t_c (31, 0.05) = 2.04) at 95% confidence interval.
Note 2: * represents $t_0 > t_c$, indicating the significance of the indicators.

integrity of examining drivers to enhance BIM-assisted O & M. The needs of the information-related factors can thus be refined to be the expectation of the readiness of detailed information.

Geometry information needs to be provided to construct an as-is BIM for the targeted building such as types and locations of building services, while non-geometry information is also required to operate and optimize the BIM-assisted O & M process. For instance, general building information is definitely significant for F10 (Specific data provision in project delivery), which is indispensable to construct the as-is BIM for O & M works. A list of manufacturers/contractors is also a

Table 6
Survey results on readiness of information in creating BIM-assisted O & M systems (1: least important, 5: very important).

Information-related factors		Detailed information	Mean
Geometry information	F10*	General building information (e.g., story, room and zone, openings, passages and protection products)	3.94
		Distribution and parameters of mechanical, electrical, and plumbing equipment	3.78
		Building components information (e.g., columns)	3.91
		Building site information (i.e., location and layout)	3.72
		Decorative material types, structural status and exterior enclosure products' information (e.g. thermal and moisture protective products)	3.47
		Types and locations of building services	4
		Logical object tree organization within BIM	3.47
		Built-in schedule of BIM	3.56
Non-geometry information	F8*	Status of data collecting and monitoring equipment (e.g., bar code/sensor information)	3.75
	F11*	Specification and attributes of information collecting techniques (i.e., type, value, limits and descriptions)	3.66
		Space management information (e.g., Space occupancy & location data)	3.56
		Building asset information (e.g., asset locations and purchase information and cost reports)	3.69
	F13	List of manufacturer/contractor (e.g., serial number, name, capability, vendor and warranty usage)	3.47
		Operation records (e.g., commission reports)	3.84
		Maintenance history and status (e.g., abandoned/removed/replaced records; maintenance inventory)	3.88
	F14	Information of enterprise resource planning in O & M company	3.22
	F20	Latest O & M manuals/specifications of BIM-assisted O & M system	3.66
	F21	FM Professionals' working schedules/specific tasks	3.28
	F24*	Modeling principle and requirements of updating as-is BIM	3.38
	F26	Professionals' experience database of dealing with emergency situations	3.50
	F27	Emergency protection information	3.88
	(first response)	Location and scale of hazard	3.69
		Emergency inventory (e.g., backup repair materials)	3.75
		Information of shelters (e.g., locations and safe pathway)	3.60

Note 1: factors with the mark "*" represent the corresponding information stored in BIM and factors without the mark mean that the information comes from O & M systems.

necessary part of F13 (Capacity to keep the integrity of historical O & M records for BIM-assisted information systems), which aids to select contractors in the building O & M process. The effective and immediate access to accurate information optimizes the time and labor productivity, and avoids the retrieving step in decision making [36].

6.2. Secondary contradictions as the external drivers of evolution between elements

The primary *contradiction* is sometimes latent and manifests itself in the secondary *contradictions*. The misfit between two interacting elements in the ASM of status 1 also prompts the formation of secondary *contradictions* in the form of concrete tensions between elements [20]. These tensions derived from secondary *contradictions* drive new items to be introduced into the ASM, reconfiguring this activity system and making it rebalanced and return to a new stable state.

In order to examine the secondary *contradictions* produced by this ASM evolution process, the 2nd round interview was conducted with the 14 experts (as introduced earlier). As stated by the original model of human activity, the core essence of human activity can be understood via the triadic relationship between a *subject* and an *object* mediated by *tools* [17]. In that way, analysis of the interviews focused on the secondary *contradictions* with *subject* or *tools*, and total six kinds of secondary *contradictions* were examined.

(1) *Subject-tools contradiction*

FM professionals' BIM experience, aptitude and capability are critical to the successful implementation of BIM in building O & M. However, according to the expert interviewees' responses, there is a gap between the professional BIM knowledge of the FM professional (*subject*) and the required ability to use BIM-assisted O & M systems (*tools*) in the current practice. The newly introduced *tools* in O & M can be a big challenge for the FM professional who cannot be adapted to changes in the evolutionary O & M process, as stated by one of the interviewees:

"…*Differing from design phases, FM professionals usually didn't get professional training and get used to current status. It is extremely hard for them to change and further accept new technologies*…"

Besides the traditional O & M skills cultivation, professional training about BIM implementation in O & M thus becomes necessary to fill the gap between the traditional O & M activities and BIM-assisted O & M activities, and also the gap between designers and O & M workers.

In addition, FM professionals' aptitude for BIM closely depends on the perceived ease-of-use and substantial benefits of BIM in fulfilling the *object* of O & M activities. Conversely, due to the lagged development of BIM in building O & M (e.g., the lack of automatic as-is BIM construction methods nowadays) [37], FM professionals still concern about user-friendly interfaces and convenience of BIM-assisted O & M system in the real-world projects, as quoted from one of the interviewees' statement below:

"*There may not exist suitable and convenient tools for the industry use… We want them but we don't know where to buy them.*"

As some of the interviewees said, companies still look for or develop suitable BIM-assisted O & M systems for the future use. Due to the slow adaptation, the O & M process still remains unchanged currently, and this status quo is expected to be continued until the appearance of new generation of BIM-assisted O & M systems.

(2) *Subject-DoL contradiction*

Responsibilities in developing and maintaining BIM should be clarified and stipulated based on the requirements of data update, built-in schedule, and phases. Nevertheless, errors and information loss often exist in the process of task handover between different phases. In the O & M phase, FM professionals often cannot get the completed building information from the upstream phases as mentioned by most of the interviewees:

"*Due to the confidentiality maybe, FM workers usually obtain inaccurate documents without completed and updated information…even they used BIM in design phases, FM workers then need to pay for this model, if they want to use it in O & M.*"

In order to use BIM in O & M appropriately, it is necessary for FM professionals to get the accurate and completed BIM. One efficient way to help them get the required BIM was put forward by our interviewees:

"…*The absent of FM professionals at design and construction leads to problematic commissioning practices…They (FM professionals) should participate in the whole process from design to operation.*"

The participation of FM professionals (*subject*) in the design and construction phrases drives the reconfiguration of *DoL*, which is also helpful to improve the integrity of building information from the life-cycle perspective.

(3) *Tools-rules contradiction*

There is a misfit between current BIM standards and protocols. The regulations (*rules*) usually specify information exchanges and updates according to local situations. It may impede the generalization of BIM in O & M within the global context, as stated by some interviewees:

"…*Since the Revit is based on international standard, engineers have to change the output, such as drawings, to keep consistent with local requirements. It is too time-consuming*…"

This incompatibility forces the *rules* to be adjusted even though they are newly established to permit the use of BIM in O & M. The *tools* should be also generated to coordinate with local construction codes/regulations and traditional analysis software applications (e.g., especially for structure analysis and O & M management) commonly used in specific regions.

(4) *Tools-community contradiction*

The applicability of *tools* used by different *communities* in the BIM-assisted O & M process is the prerequisite of the successful evolution from the traditional O & M to the advanced O & M. The choices of *tools* usually depend on the different roles and requirements of *communities* in the O & M process, such as owners, contractors and consultants. However, a misfit between *tools* and *communities* can be often found in the current practice, as stated by two of the expert interviewees:

"*It's good to use BIM in O & M, but we don't know which kind of BIM O & M system should be bought or developed if our company determines to use BIM in the O & M process.*"

"…*However, I cannot find one suitable BIM O & M system and corresponding techniques for my team nowadays…We may need some data that other teams don't want…They (BIM O & M systems) are different (and) dependent on the specific needs from different (system) users.*"

Many BIM-assisted O & M systems in the current market cannot guarantee to meet specific requirements of the specific *community*. Consequently, the contradiction between *tools* and *community* makes it unavoidable to regenerate BIM-assisted O & M systems with the consideration of certain needs from different *communities*.

(5) *Rules-community contradiction*

For the novel BIM-assisted O & M process, it is widely recognized that there is a lack of clarification about O & M participants' rights and obligations (*community*) in insurance and contracts (*rules*). Disputations can thus be resulted in as worried by some of the interviewees such as:

"…*In our company*, *BIM is a beginning for all staff. Unfortunately*, *we didn't have standardized contracts or good samples to regulate their duties yet*…"

Therefore, standardized contracts (*rules*) are driven by this secondary *contradiction* between *rules* and *community* to clarify the specific rights and obligations of each stakeholder (*community*), including the building model ownership, intellectual property, and authorized use of BIM with corresponding information in O & M. Risk allocation and the regime of liability are also needed to be pre-determined in insurances (*rules*) to release this concrete tension.

(6) *Rules-DoL contradiction*

Similar to the secondary contradiction between *rules* and *community*, there is also a lack of guidance (*rules*) for work divisions (*DoL*) in the process of BIM-assisted O & M. As the novelty of the O & M process, the BIM-assisted O & M system can make workers with no experience of using BIM confused with the newly established schedule and newly proposed skills. This phenomenon urges the update of *rules* to be adapted to the new work assignments caused from the use of BIM in O & M.

7. ASM-based driver model of evolution

Based on the *contradictions* (primary and secondary) identified within the context of the activity theory, a driver model of evolution can thus be established to clearly show the mechanism of how these drivers help enhance the implementation of BIM in the building O & M (Fig. 6). Six elements of the ASM, 26 primary *contradictions*, and six secondary *contradictions* are all involved in this model.

Among these drivers, the 26 primary *contradictions* in terms of five elements can act as internal drivers to facilitate the self-adaption and self-innovation within the corresponding industry and the research field. This kind of drivers are thus defined as active and innovation-oriented drivers. All the adjustments and changes are derived from the specific element itself within the context of the BIM-assisted O & M but without considering interactions between elements. The readiness of the factors in Table 5 and the readiness of the information in Table 6 provide the feasible ways to improve the performance of specific elements in the O & M process, aiding in the evolution from the traditional O & M to the BIM-assisted O & M. For instance, as expected in the F8 of *tools*, the seamless information exchange from information collection tools (e.g., camera) to the BIM-assisted O & M system could inspire the research and applications of as-is BIM.

Based on the adjustments triggered from the primary *contradictions*, the six secondary *contradictions* can act as the external drivers derived from the relationships between interacting elements, to make the interacting elements coevolve to keep the balance and stability of the relationship. However, different from the internal drivers, the external drivers are mainly based on the internal drivers initially happened, and regarded as passive and demand-oriented drivers. In this way, the changes happened in the targeted elements are resulted from the needs and expectations from the interacting elements. For instance, FM professionals need to learn how to use BIM-assisted O & M systems under the pressure of the gradually popular use of BIM in O & M (*subject-tools*).

The internal drivers (primary *contradictions*), which are active and

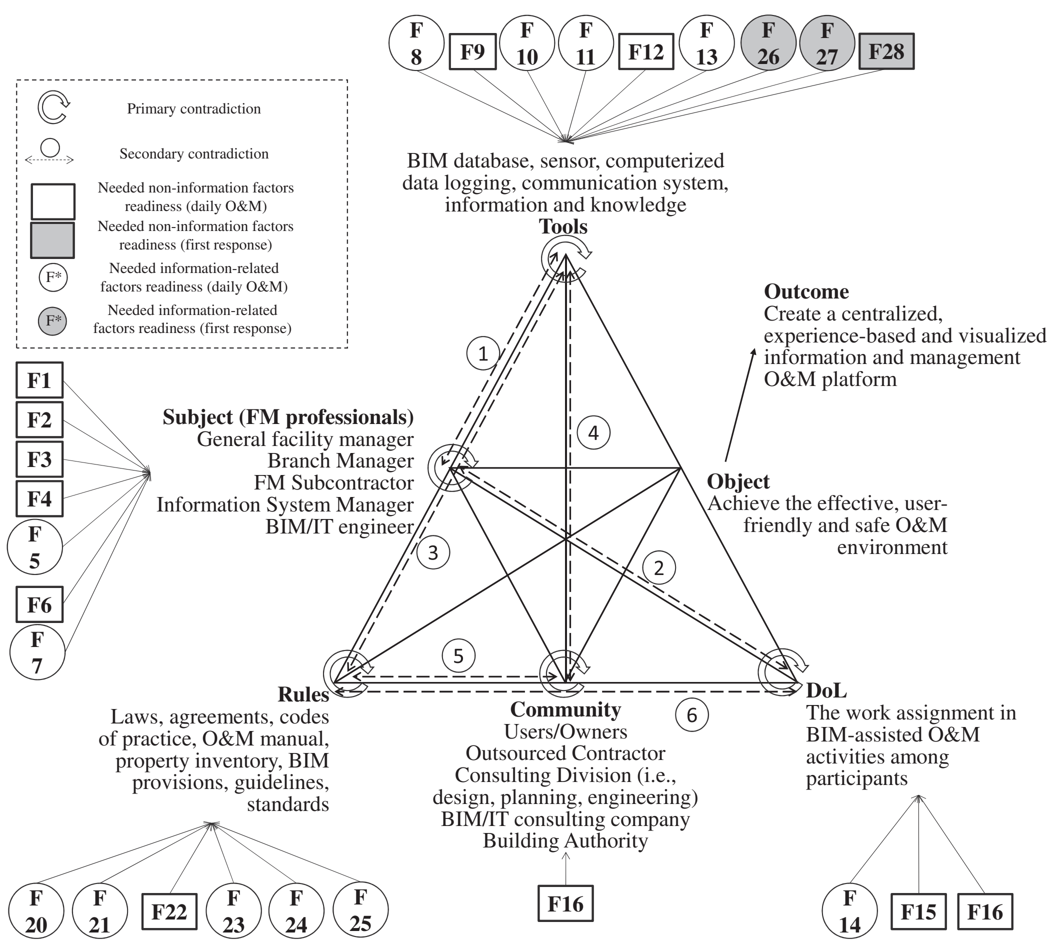

Fig. 6. ASM based driver model of evolution.

Table 7
Examples of policy initiatives for BIM implementation in O & M.

Country	Initiative/target/strategies	Reference
HK	Harmonize BIM implementation across a spectrum of design, construction, and operation disciplines, and explore the use of BIM as an asset management tool	[45]
	Link an as-built BIM database to an organized building management system, and further facilitate the O & M asset management	[46]
Singapore	BIM Execution Plan for data requirement and deliverable of as-built model used for O & M	[47]
	Provide a benchmark for the attributes of BIM deliverables, process of BIM creation, and maintenance at O & M stages	[48]
Australia	Speed up the BIM use in the management of existing buildings, taking the Sydney Opera House as an example	[49]
US	GSA BIM guide for facility management	[50]
	BIM & facility electronic operation and maintenance support information (eOMSI) program and NAVFAC's phased implementation plan	[51]
	National BIM Standard from project planning and designing through construction and operation	[52]
UK	Optimize the operating performance within the operational budget, aiming at achieving the mandate BIM level 2 in 2016	[53]
	Increase BIM Level 2 maturity across government, gradually move to BIM Level 3, in order to further improve construction and O & M	[54]
Germany	Guidelines on the use of BIM-assisted methods in Germany from building planning to operation	[55]
China	Proposal on enhancing the BIM implementation in project design, construction, operation and maintenance	[56]
	Establish government policy systems and industry guidelines for BIM application from building design to operation stage by 2020	[57]

Table 8
The systematic recommendations based on the ASM-based driver model.

Recommendations	Enhanced drivers		
	Primary		Secondary
1. Clear mission statement among *subject*	*Object*	Outcome	–
2. Confirm FM professionals' hiring strategy	*Subject*	F2, F5	*Subject-Tools*
3. Determine FM professionals' training plan		F1, F2, F4, F7	
4. Establish reward and punishment system		F3, F6	–
5. Define the upper management strategy			–
6. Design mechanisms/gateways entering and accessing data	*Tool*	F8, F26	–
7. Choose assisted techniques/algorithms		F9, F11, F12, F28	–
8. Confirm suitable hardware and software			–
9. Update or construct as-is BIM; Enlarge and enrich the library of BIM families		F10	–
10. Maintain accurate and complete database		F13, F27	–
11. Set strategies of shifting/sharing risks	*DoL*	F14	*Rules-DoL*
12. Confirm FM professionals' insurances			–
13. Confirm delivery approach and procedure		F15	–
14. Clarify participants' responsibilities, duties, and communication approaches		F16	*Subject-DoL*
15. Prepare checklist of BIM/IT consultants and verify their professional level	*Community*	F18, F19	*Tools- Community*
16. Set benchmarking projects and relevant cases	*Rule*	F20, F21, F22, F24, F25	–
17. Confirm BIM implementation guides, standards, protocols and quality control plans			*Tools-Rules*
18. Confirm BIM-assisted O & M manuals			*Tools-Rules*
19. Confirm budget and cost plan			–
20. Adopt legal framework and contract templates towards BIM-assisted O & M			*Rules- Community*
21. Determine information exchange standard		F23	–

innovation-oriented, and the external drivers (secondary *contradictions*), which are passive and demand-oriented, can work in tandem to initiate, deliver, and enforce changes in the evolutionary process from the traditional O & M to the BIM-assisted O & M. This ASM-based driver model can indeed effectively depict the mechanism of enhancing the implementation of BIM in the building O & M (Fig. 6).

8. Discussions and recommendations

With the ASM based driver model of evolution, the most efficient way to promote the adoption of BIM in O & M is to reinforce the drivers, via which the evolution towards the BIM-assisted O & M can be achieved. Many organizations and researchers have made efforts to trigger or accelerate this evolution from social, political and technical perspectives. More specifically, new opportunities and corresponding specific recommendations are also needed to put forward from the perspective of FM professionals based on the newly established ASM-based driver model of evolution.

8.1. Efforts made to enhance drivers

8.1.1. Education and public awareness

The following are examples of projects, programs, events, and professional qualifications that have been developed and conducted in many different countries in order to increase public awareness and education of adopting BIM in O & M:

- Demonstration projects: The BIM-assisted O & M pilot project [38]; Sydney Opera House in Australia [39]; Administration building renovation (University of Chicago) and Wisconsin Energy Center pilot project in US [40]; Northumbria University city campus in the UK [41].
- Training course and workshop for professionals: Hong Kong BIM implementation, integration and collaboration programs [42]; Australia BIM Initiative stakeholder consultation workshops and Facility Management Association (FMA) training programs [39]; US training programs for BIM-integrated asset management [40].
- Professional qualification: US professional qualifications for BIM-integrated asset management [40]; UK BIM4FM membership [41].
- Global conference and public seminar: 7th Greater Pearl River Delta Conference on building O & M [43]; Seminar on IT, BIM, innovation and FM center for facilities management [44].

In addition to providing these opportunities and establishing long-term targets (*outcome*) in O & M, universities in different countries can also consolidate the education of BIM in O & M. The primary step is to achieve common awareness of the meaning of BIM-assisted O & M across *subject*, *community* and further the entire AEC industry.

8.1.2. Policy supports

Nowadays, BIM implementation has begun to extend in the O & M phase, especially since 2014 (Table 7). Various standards and government policies (*rules*) from different countries have presented their initiatives towards BIM in O & M, but *rules* in this field are still under development. From the nation-wide development level (*outcome*), development strategy, direction and overall management should be highlighted and strengthened by the construction department and the national development department. From the region-wide development level (*object*), detailed development plans, scientific regulations and standards (*rules*) of BIM in O & M are significant for promoting BIM implementations. As shown in Table 7, it is still lack of practical and comprehensive *rules*. It suggests that competent departments of construction, experienced industries and universities or relevant research institutes cooperate to be the leader, and guide for the planning, policy and regulation formulation and implementation of BIM-assisted O & M management. Furthermore, divisions of responsibilities (*DoI*), performing as contracts and legal frameworks (*rules*), should also be updated and set as a benchmark for the whole AEC industries.

8.1.3. Technical innovation

In recent years, various BIM-assisted O & M systems and algorithms (*tools*) have been developed. For instance, Hu et al. provided virtual scenes for various participants to communicate, cooperate and share data through using macro-, micro- and schematic-scale information models of the mechanical, electrical, and plumbing (MEP) components [58]. In order to effectively integrate data from heterogeneous systems in O & M, Kang and Hong proposed a BIM/GIS-based information Extract, Transform, and Load (BG-ETL) architecture for FM [32]. In emergency situations, Li et al. introduced a schema for locating first responders at fire emergency situations using an environment aware beacon deployment algorithm [59].

Technical innovation and development provide more opportunities to enhance BIM implementation in O & M. However, an evaluation framework is needed to assess overall performances for these developed systems, from cost, practical possibilities and convenience aspects. Furthermore, technical standards are also urgent, which aim to clarify and specify the quality index of technologies' performance, test and inspection methods, and potential relevant information management systems.

8.2. Specific recommendations for FM professionals

The O & M professionals have started to believe that there is great potential and value of implementing BIM, but how to begin and use BIM is the primary issue that confused them [60]. Hence, on the basis of the ASM-based driver model, a set of recommendations is created as shown in Table 8. The recommendations can be an assessment outline to evaluate their BIM-assisted O & M systems and also a possible solution for FM professionals to consider their BIM execution in a comprehensive view. For instance, organizations could establish FM professionals' training plan, and a reward and penalty system to decrease the secondary contradiction between *subject* and *tool*. All these findings may aid enhancing knowledge of FM professionals (*subject*), regulating their duties and behaviors (*rule* and *DoI*), improving the efficiency of O & M management (*community*) and strengthening company's competitiveness (*tool*).

9. Conclusions

This research provides a comprehensive and comparative analysis of current practices of building O & M without and with BIM assists in a systematic and dynamic way, based on the activity theory, and further the drivers with recommendations to facilitate the implementation of BIM in O & M. Two process models under different statuses (i.e., without BIM and with BIM) and corresponding ASMs have been established, respectively. The ASM based driver model of evolution has been further developed to clearly depict the mechanism of how the internal and external drivers trigger and accelerate the transition from the traditional O & M to the BIM-assisted O & M. The research has identified total 26 primary *contradictions* represented as the readiness of factors and explained by the readiness of information as the internal drivers within elements, while 6 secondary *contradictions* have been identified and examined as the external drivers between elements. With the context of social, political and technical influences, 21 recommendations based on ASM have been proposed from the general to specific perspectives to enhance and intensify the determined drivers of evolution, which aims to achieve successful BIM-assisted O & M eventually. This study has significant implications for building O & M, especially for BIM-assisted O & M. The results provide a consolidated way for both researchers and practitioners involved in BIM or O & M to have more detailed insight into the status of the current practice, expectations towards BIM-assisted O & M, and the key drivers and mechanism of the transition, which therefore is meaningful to the promotion of BIM in O & M to achieve the effective, user-friendly and safe O & M environment.

There are limitations in this study. One limitation pertains to the sample size. We collected valid surveys from 32 respondents around the world. A larger-sized survey will enhance the reliability of the ASM. Another limitation is the nationalities of experts in the interview part. Although the interview participants are all experts in O & M from USA, UK, Korea, Hong Kong and Mainland China, larger-scaled multinational interviews will strengthen the validity of this developed ASM-based driver model of evolution in O & M. As future work, it is recommended to conduct surveys with more experts in academia and the practice from other countries to reinforce and validate the model, and further analyze the significances of each readiness of factor in ASM.

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