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The use of a BIM-based framework to support safe facility management processes

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ABSTRACT

Maintenance personnel in the field of facility management (FM) are at constant risk of electrical shock, falls, crushing, cuts and bruises, and as a result, have a much higher rate of injury and illness than the national average. Case study analysis confirms that many recorded accidents could have been avoided had the victim followed appropriate hazard mitigation steps to safely execute a FM task. Currently, safety information is conveyed through training seminars, documents, and meetings. This information, although comprehensive, often remains fragmented among multiple resources. Research has shown that the more time and effort an individual must spend obtaining information, the less likely they are to retrieve the information and obey the stated warnings, directly relating to injuries and fatalities. This research attempts to mitigate these issues by describing current market trends, available technologies, and limitations. The paper presents a BIM-based framework to support safe maintenance and repair practices during the facility management phase, through safety attribute identification/classification, data processing and rule-based decision making, and a user interface. By developing a BIM-based framework for FM safety, an underutilized/under-researched usage of BIM is being explored.

1. Introduction

1.1. Background

Buildings in the United States and around the world are becoming increasingly complex, utilizing sophisticated technologies for communication and operational control. The role of facility management (FM) staff is critical to the planning, maintaining, and managing of these complex facilities [1]. As skilled professionals, FM staff use knowledge in multiple disciplines such as mechanical, electrical, plumbing, and fire protection (MEPFP) to ensure the functionality of the built environment [2]. Often, the complexity of the systems will dictate the requirements for FM staff and the expertise areas that are required for the management of the facility.

Due to the maintenance and repair requirements of these facilities and the time sensitivities associated with these tasks, workers in this field are at high risk of injury including, electrical shock, falls, crushing, cuts, and bruises. As a result, FM personnel in the United States have a much higher rate of injury and illness than the national average when compared to all other fields of employment (See Fig. 1) [3]. Within the private sector from 2008 through 2012, FM employers recorded 98,420 cases of occupational injuries and illness, with 26,190 cases requiring a minimum of 31 days away from work [4–8]. In the same time frame, 293 people lost their life in the field of facility management, also referred to as General Maintenance and Repair [9–13]. This number accounted for roughly 1.3% of all work related fatalities in the United States and has shown an increase of 64% from 2008 to 2012 (Fig. 2). Case study analysis of the Fatality Assessment and Control Evaluation Program (FACE), issued by The National Institute of Occupational Safety and Health (NIOSH), confirms that many of the recorded accidents could have been avoided had the victim followed appropriate hazard mitigation information to safely execute the FM task, defined in this research as *safety protocol*.

To mitigate some of the risks associated with FM tasks and to comply with many federal, state, and local laws, organizations provide job specific training and numerous safety specific documents to protect their FM employees [14]. These are proven and effective methods for the protection of staff, but require the information to be utilized comprehensively. In other words, no single training seminar or safety document supersedes the others. This requires the FM personnel to comprehend all the safety information collectively and enact the applicable safety protocol with each FM task. With majority of onus on the worker's interaction with the safety information, it is not surprising that human error is the cause of 70–80% of all operational accidents [15].

This research attempts to mitigate the issues presented in Section 1 by describing current market trends in relevant FM safety information development, delivery, and storage (Section 2), available technologies for safety storage, retrieval, presentation, and associated analysis of these technologies (Section 3), and presents a framework to support

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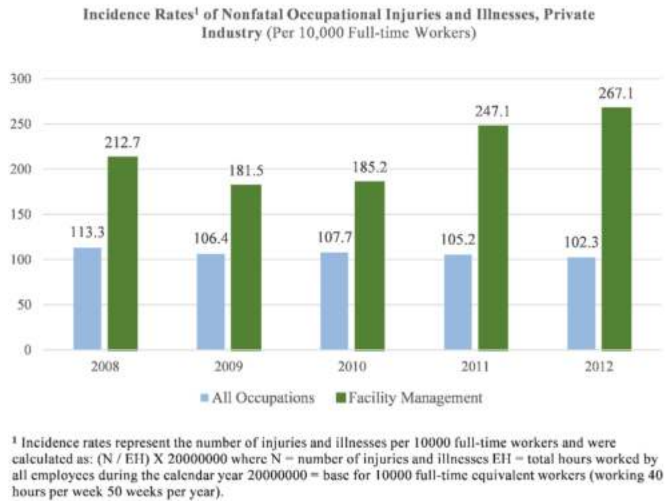

Fig. 1. Comparison of incidence rates.

safe maintenance and repair practices during the facility management phase (Section 4).

2. Relevant FM safety information

Comprehensive safety information is typically available within an organization; however, this information is often uncategorized and fragmented among multiple resources that would need to be referenced prior to a FM work activity [16,17]. Research has shown that the more time and effort an individual must spend obtaining information, the less likely they are to retrieve the information and obey the stated warnings [18–20]. Conversely, minimizing the amount of time and effort to the lowest possible level of information retrieval, has shown a much stronger likelihood of safety protocol implementation [20]. This is especially important in a field where tasks are often time sensitive. Working under the stress of too many work orders and short deadlines results in rushing, which has been shown to be directly correlated to occupational injuries and fatalities. According to The Lawrence Berkeley National Laboratory [21], "Injuries due to time pressure are most often the result of a conscious or semi-conscious decision on the worker's part to circumvent a known preventative measure to a known safety hazard in the interest of getting the task done on time or rushing to keep ahead of a process following close behind." The inconvenience of having to retrieve uncategorized safety related information from a number of fragmented sources, retards the FM task, requiring time sensitive activities to be rushed, and often distracting attention from hazards that would normally be recognized.

Exploring which contract entities input safety data, when the data are presented, where it is stored, and how it is extracted, provides insight into the fragmentation of current market safety protocol. This research explores a potential solution to mitigate the uncategorized and fragmented nature of current market safety information by providing job specific safety protocols at the lowest possible level of information retrieval through the use of a singular BIM-based framework. The framework acts as an intermediary between the stored job specific safety protocols and the FM personnel assigned to the task.

2.1. Safety information sources

Information that is applicable to the safe maintenance of a facility comes from a number of sources. This information is often presented by the contract entities, through a number of contract required documents throughout the buildings lifecycle, as presented in Fig. 3. Design drawings, specifications, and 3D models provide information such as powers sources, disconnect locations, elevations, etc., and are often developed during the design phase. When architects and/or engineers (A&E) begin to design a building, the routing of power, proximity of disconnects, the number of isolation valves, the elevation of equipment components, and many other considerations, all affect the maintenance requirements during the FM phase. A conscious understanding of this cause and effect and the subsequent design in support of downstream lifecycle phases is known as Prevention through Design (PtD) or Design for Safety (DfS) [22–24]. The use of PtD/DfS is a powerful tool to improve accident mitigation; however, has historically been focused on the construction phase and less on FM.

Along with the considerations made by the design team, the capturing of supplier/contractor procurement decisions within a project could also play a significant role in the development of FM safety protocols. Contractor selection of a manufacturer for procurement of materials and/or equipment results is a substantial amount of applicable safety information that is presented through submittals and O&M manuals. Information such as maintenance cycles, maintenance protocol, required tools, and contact information, all play a role in the downstream development of a safety protocol. Recently, with a focus on BIM-FM, FM personnel have become involved in projects during the design and construction phase in order to aid in this type of decision making. This is often achieved through specific equipment specifications or collaborations with suppliers/contractors.

In addition to project specific information, safety information applicable to the FM staff will come from organizational policies and procedures. Through safety meetings, checklists, handbooks, manuals, and legal precedence, the internal requirements for the maintenance of a

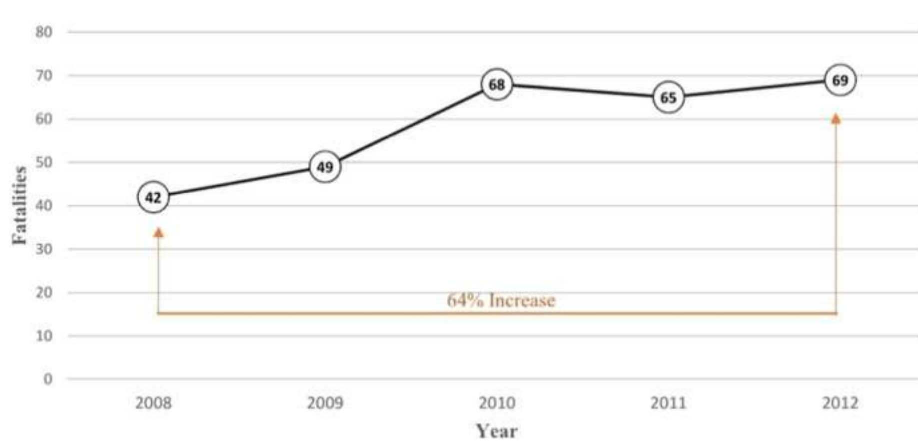

Fig. 2. FM fatalities from 2008 through 2012.

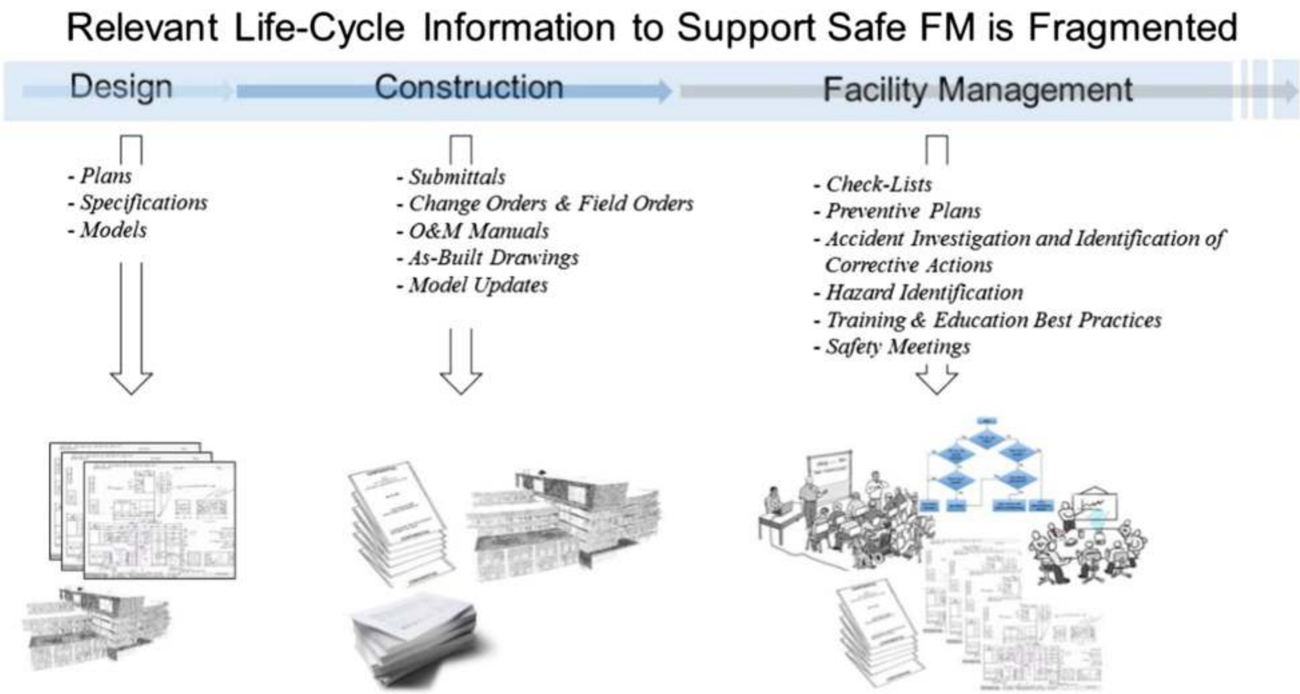

Fig. 3. Safety documentation sources occurring throughout the facility lifecycle.

facility play an integral part in the development of safety protocol. As the employer of facility management staff, the owner/facility manager is ultimately responsible for the safe maintenance of the facility. Failure to properly educate staff or maintain a safe working environment could result in worker's compensation claims and/or litigation [25].

2.2. Fragmentation of safety related information to support facility management

Research has shown that the more time it takes a person to obtain safety information, the less likely that individual is to reference or retrieve the information and obey the stated warnings [18–20]. In facility management, safety related information is fragmented among multiple resources that are developed throughout the lifecycle of a project, creating inefficiencies in the procurement of information. When a piece of equipment requires maintenance or repair, the FM personnel will need to address all of the safety concerns that are applicable to the maintenance process of that equipment. This will likely require referencing multiple documents to obtain a comprehensive understanding of the task. The inconvenience of having comprehensive safety information scattered through multiple documents, coupled with the often present time sensitivity inherent to FM tasks, can result in FM personnel bypassing the retrieval of applicable information, exacerbating the likelihood of work-related fatality, injury, or illness.

Recently, a significant push has been made to incorporate operations and maintenance information into BIM models and/or computer maintenance management systems (CMMS) in order to consolidate the information to improve efficiency in retrieving information. Through the use of BIM interoperability, virtual databases, and add-ons such as COBie, an improvement in O&M storage and retrieval has been achieved. However, this information has not focused on the storage and retrieval of safety information, and although there may be a small percentage of applicable information overlap, relevant safety information often remains unorganized and uncategorized. Nevertheless, utilizing these existing systems for storage and retrieval of relevant safety information remains a viable and promising avenue of research. As shown by Meadati & Irizarry [26], building information models can act as a single, centralized database for knowledge storage and retrieval.

The following example presents a typical FM task that a worker may encounter at a large utility or industrial plant. This example is intended to present the applicable safety information required for the activity and where that information is typically located.

2.2.1. Project example

A facility management worker receives an annual maintenance request to assess a Motor Control Center (MCC). An MCC is an assembly of combination starters in a single enclosure that contains motor starters, fuse or circuit breakers, and a disconnect [27]. These are commonly found in commercial or industrial applications where a number of motors are present and the owner wishes to consolidate the motor controls into one housing.

In this scenario, the FM worker will need to review the design drawings/specifications, 3D model, and/or CMMS system to find information such as power source, components, disconnect location, and schematics. This will provide a "lay of the land" and allow the FM worker to prepare for the MCC prior to opening the cabinet. For information such as MCC maintenance protocol, safety precautions (such as arc flash), warranties, and manufacturer information, the worker will need to review both the O&M Manual provided by the contractor/manufacturer and the CMMS system. Information within the O&M manual will often incorporate operations as well as some equipment specific safety information. Finally, the worker must abide by the high voltage gear safety protocol established by their organization. This information is typically available in a number of safety manuals, meeting minutes, OSHA documents, or adopted safety literature. All of this information will need to be extracted in order to develop of a comprehensive safety protocol that must be enacted by the FM worker to maintain a safe working environment.

Although some of this information may be stored in a virtual database or 3D model, it is unlikely that comprehensive, job specific safety related information would be available. By identifying and consolidating the safety information relevant to the FM task, the convenience in accessing and obtaining comprehensive safety protocol for the MCC is greatly improved. Minimizing the FM worker's inconvenience and providing a singular point for interaction would result in a greater likelihood of reference and safety protocol execution.

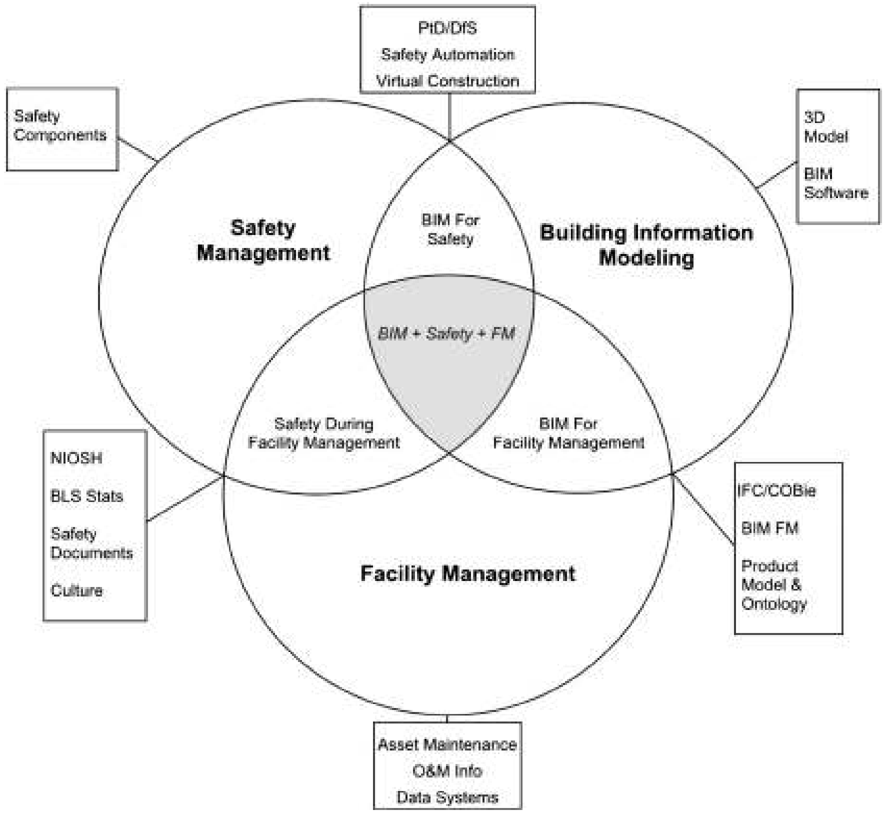

Fig. 4. Literature analysis Venn diagram.

3. Current trends and available technologies

This study utilizes a literature review and analysis to identify current market trends and available technologies to support the current need for facilitating necessary information to perform FM operations in a safer environment. In addition, a new method for FM workers to interface with applicable safety protocol is proposed.

By exploring the topics of safety during facility management, the use of BIM for facility management, and the use of BIM for safety, the intersection of these topics was substantially insufficient creating a gap in knowledge as shown in Fig. 4. These detailed research concepts were developed from three core concepts of facility management, safety management and BIM. A thorough understanding of the core concepts and sub-concepts of this research is necessary to identify the current processes utilized during facility management activities.

In order to obtain a detailed understanding of current trends and research, this literature review utilized online resources such as OSHA, facility management, computer engineering, government websites, and peer-reviewed journal articles on the various topics. Additionally, discussions with industry experts were executed to provide a general understanding of topics. Table 1 presents the resources utilized in each section of the literature review. The study will critically analyze the three areas stated and then comprehensively review and analyze the intersection of these three areas.

Exploration of safety during facility management, the use of BIM for facility management, and the use of BIM for safety provided a comprehensive understanding of current market trends and research. A comprehensive, critical analysis of these areas as individual sections, allowed the research to identify overlap, eventually exposing a research potential. The proposed research framework will address this potential and present a solution to fragmentation and safety concerns within FM by incorporating BIM + Facility Management + Safety. Fig. 4 graphically presents the literature review approach that this study utilized to identify the research potential. Utilizing the information obtained through existing literature and current market trends aids in the development of the applicable safety protocols and proposed research framework.

3.1. Safety during facility management

For FM staff, a thorough understanding of potential health risks that may be encountered during a work activity and the safety protocol utilized to mitigate the risks is of paramount importance. To remain proactive, many organizations maintain injury and illness prevention programs to reduce occupational injuries, illnesses, and fatalities [28]. These documents, although good for general safety information, are not tailored to specific work activities that a facility management worker would encounter on a daily basis. Legally, an organization is required

Table 1
Literature review resources by category and resource type.

Safety during facilities management	BIM for facility management	BIM for safety
Online resources (14) Journal articles (6) Industry expert discussions (4) *Included: Engineering Firm, Major Utility Owner, University FM Staff, Facility Safety Expert*	Online resources (5) Journal articles (21), book (1) Industry expert discussions (4) *Included: BIM Software Developer/User, BIM FM Consultants (3)*	Online resources (3) Journal articles (22) Industry expert discussions (1) *Included: Professor (Safety Expert)*

to, “satisfy the ever-increasing number of federal, state, and local statutes relating to institutional health, safety, and the environment” [29]. To comply with these requirements, many organizations develop risk management or safety handbooks specifically for the FM department. These handbooks are developed to provide general safety guidelines for FM staff including information on forklifts, personal protective equipment, rigging, scaffolding, and the like [30].

In addition to safety handbooks and prevention programs, many FM departments will hold, daily, weekly, or monthly safety meetings to discuss safety concerns, incidents, accidents, and information on safety topics [31]. Similar to safety handbooks, these meetings are an effective method for conveying general safety topics or reactively discussing an incident, but are often executed in a lecture format that has been shown to be less effective than an active learning approach. Safety meetings, also known as “toolbox talks” or “safety talks,” typically present OSHA safety instruction, jobsite hazard training, and general safety awareness for items like ladder safety, eye protection, and working at elevation [32,33].

To address specific work activities, some organizations have developed non-specific checklists that are reviewed prior to the initiation of an FM task [34]. Checklists can be an effective tool if utilized correctly; however, there are a few inherent issues with relying solely on safety checklists. Table 2 evaluates the pros and cons of utilizing safety checklists.

Safety checklists can be a valuable tool, but as a non-specific, standalone document they rarely include enough information to fully encompass the dangers associated with specific job activities [35]. Regardless of the work activity a facility management worker is executing, the individual should have a working knowledge of the organizational, departmental, and individual safety requirements identified by that worker's company.

In addition to documentation, FM departments typically require new and existing employees to attend training seminars. Training is an essential part of implementing accident prevention and gives a strong foundation for general safety processes and requirements [34]. Training may also be required to comply with federal, state, or local law. Federally, the Occupational Safety and Health Act of 1970 was developed, “to assure safe and healthful working conditions for working men and women” [36]. Although the Health Act of 1970 does not specifically require employers to instruct or train employees, Section 5(a)(2) does require each employer to, “comply with occupational safety and health standards promulgated under this Act.” A review of individual safety and health standards yields more than 100 Acts that do contain training requirements [14]. Recently, the United States Government passed the “Federal Buildings Personnel Training Act of 2010.” This act requires personnel performing building operations and maintenance in federal buildings to complete comprehensive training and be able to demonstrate “competency relating to building operations and maintenance, energy management, sustainability, water efficiency, safety (including electrical safety), and building performance measures” [37]. This law was enacted to protect the citizens of the United States, whose tax money is utilized to operate federal buildings, by requiring minimum competencies of the individuals responsible for building performance [38]. The safety portion of this bill protects the American taxpayer from worker's compensation claims and lawsuits.

Table 2
Pros and cons of safety checklists — adapted from [35].

Pros of safety checklists	Cons of safety checklists
Simple form of hazard analysis	May be irrelevant for complex equipment
Easy to use	Limited to expertise of its author(s)
Quick results, allows work to get underway	Hazard identification is subjective

3.1.1. Safety culture and human factors

Although this research is not intended to address safety culture and human factors, to obtain a comprehensive view of safety within the field of FM, the perception of safety within an organization must be taken into account. The way FM staff approaches the safety protocol of work activities will certainly depend on experience, training, and available documentation, but will also depend on the worker's values, attitudes, and behavior towards health and safety [39]. Staff attitudes and behaviors towards safety, also known as *safety culture*, is often a direct reflection of the organization's culture [40–42]. Organizations that take a proactive approach towards the safety culture are often more risk aware, informed, honest, adaptable, and resilient [43].

The role that human decision making plays in the implementation of safety protocol cannot be understated. Human error, “a deviation from the performance of a specified or prescribed sequence of actions,” accounts for 70–80% of operational accidents [15]. This deviation can be due to any number of reasons, from an increase in system complexity to new hazard types. Similar to the role of safety culture, to minimize the amount of human error within a system, effective approaches will address the goals and the motives behind why a human approaches a solution, as well as how that information is presented.

3.2. BIM for facility management

With all the success that BIM has experienced during the design and construction phase, efforts to transfer information to the facility lifecycle phase is in its infancy. The utilization of BIM for facility management, also known as BIM FM, is a relatively new usage of BIM. Prior to the mid-1990's, to fully utilize the design and construction information during the FM phase, the issue of data transfer needed to be resolved. With dozens of software programs on the market, developed by a number of different vendors, interoperability between them was non-existent. In 1995, a consortium of twelve companies called the Industry Alliance for Interoperability (IAI) developed an object-based data model that utilized non-proprietary translators that could read the building information across a number of software platforms. The resulting data model was known as the Industry Foundation Classes or IFC [44]. Today, IFC is published, maintained, and updated by the buildingSMART alliance. As a vendor-independent, open standard format, IFC is supported by roughly 150 software applications worldwide [45,46]. The interoperability of the IFC format allows designers, contractors, and owners to utilize different software through the many phases of the building lifecycle without losing data due to the proprietary nature of individual software.

In December 2005, the National Building Information Model Standard (NBIMS) Development Team introduced a component to the standard known as the Construction Operations Building Information Exchange or COBie [47]. COBie was released to improve how information is captured during the design and construction phases, and then turned over to the owner for operations and maintenance. COBie utilizes the open data format provided by IFC to attempt to bridge the gap between design, construction, and O&M by mapping commonality within the FM process. By approaching FM activities with an open source, interoperable set of standardized attributes, users can then customize the data to suit their facility needs.

Utilizing IFC and COBie for interoperability has allowed project teams to transfer design and construction data to owners at the beginning of the FM phase; however, this remains an uncommon occurrence. As Lucas [17] described, “the AEC (Architecture, Engineering, Construction) industry information exchange through the facility lifecycle is fragmented and the facility management phase of the lifecycle remains the most disconnected from the rest.” A study conducted by the National Institute of Standards and Technology (NIST) states that, “An inordinate amount of time is spent locating and verifying specific facility and project information from previous activities” [48]. Even in scenarios where the data from design and construction is readily available, FM software relies on “hard data entry” for the transfer of data [49].

Additionally, data coming from diverse native file formats are unorganized and scattered, for example, under various tabs within a single Navisworks file. Other issues such as model updates, a shortage of BIM skills, a lack of collaboration between project and end user stakeholders, and interoperability, all contribute to the low utilization of BIM for FM [45,49–51].

In today's market, owners, researchers, and software developers have all realized the issues related to data transfer from the end of construction to the O&M lifecycle phase. Owners have attempted to mitigate the issues with data transfer by developing BIM-FM requirements and writing detailed contracts, BIM oriented specifications, and issuing BIM Management Plans that provide project specific methods in order to deliver facility data in a format that the owner is able to utilize. Researchers such as Lucas [17], Kiviniemi and Codinhoto [52], Lin and Su [53], and others have attempted to synthesize and bridge the gap in data loss between the end of construction and the beginning of the FM phase in complex buildings. By utilizing data exchange frameworks, analysis, and modeling, researchers are pursuing a seamless interaction between construction and post-construction phases. Software developers such as Bentley Systems are developing intelligent models (i-models) to intake, organize, and present equipment and facility data from a number of varying software sources into a single model [54]. Middleware solutions, such as EcoDomus, act as a bridge between a BIM model or database and an application. These systems have shown promise for sizeable organizations but are relatively expensive [55]. Cheaper alternatives, such as Navistools, Datatools, and iConstruct, are application developments that target a specific task, but are not comprehensive enough to service all data transfer needs.

In addition to data transfer, facility management data systems can be utilized to aid FM departments in maintaining and tracking assets, issuing work orders, and executing a number of other FM functions. Facility management and operations staff work with a variety of tools ranging from manual paper and spreadsheets, to more advanced computer based systems including Computerized Maintenance Management Systems (CMMS), Computer-Aided Facility Management (CAFM) tools, and Building Automation Systems (BAS) [55].

Computerized Maintenance Management Systems (CMMS) are utilized by facilities maintenance organizations to record, manage, and communicate their day-to-day operations [56]. CMMS can be deployed for asset management, inventory control, generation of service requests, managing work orders of different types, and tracking the resources (time and costs) of services and materials used to complete work orders [45,55]. Computer-Aided Facility Management (CAFM) systems integrates a Computer-Aided Design (CAD) graphics module and a relational database software to provide various facility management capabilities [56] including space management tools (e.g. administering room numbers, departments, usable heights, room areas etc.). CAFM systems also provide means to collect data from a variety of sources through technology interfaces to other systems (such as CMMS) or human transfer processes. Integrated Workplace Management Systems (IWMS) have many of the functionalities as a CAFM system with an emphasis on estate portfolio and space management [57]. Building Automation Systems (BAS) are centralized, interlinked, networks of hardware and software, which monitor and control the facility environment to ensure the operational performance of the facility as well as the comfort and safety of building occupants [58]. Most of the automation system is behind the scenes as hardware devices mounted to equipment or hidden underfloor or in the ceiling. Some personalized control can be made available through thermostat-like devices. From a central management perspective, the BAS resides as software on an operator's computer or is available as a web page. Even with the wide variety of software/hardware applications available to service facilities management needs, there is no single application that would encompass the diversity of all FM requirements [59].

Although the systems and research being utilized are young and still problematic, studies of organizations that have successfully integrated BIM FM to some extent, often sizeable government organizations, have shown promising results for utilizing BIM throughout the facility lifecycle. One such study shows a Return on Investment (ROI) of about 64%, with a payback period of 1.56 years [45]. These savings are realized through the intelligent use of the data collected through the design and construction phase and the integration of BIM FM to make better and faster maintenance decisions based on the data.

As owners, researchers, designers, and developers continue to make strides in the use of BIM throughout the building lifecycle, emerging technologies could help support the complex and data-driven information required for FM [45]. Cloud computing, mobile computing, RFID/QR technologies, augmented reality, and sensor data could all be incorporated into BIM models to provide real-time information. Additionally, the continued research into semantic interoperability and the use of semantic tools (extended algorithms, weighing and ranking systems, etc.) and ontologies will provide greater knowledge management for personnel. A number of resources into current and future applications of O&M information and technologies are presented by Sapp [56] in the Whole Building Design Guide.

3.2.1. BIM/product model and ontology

A product model uses an object-oriented data structure to formally classify information to support the exchange of data through a mechanism [60]. The mechanism utilized within a product model is an ontology, a set of translations for how information behaves within a system [17,61]. Ontologies are often developed to identify domain specific vocabulary, structure domain knowledge, and exchange information [62]. By executing an ontology within a product model, a conceptual schema or framework of data can be properly structured and stored.

The use of ontologies and product models within construction has often been used to synthesize the cause-consequence sequences that are prevalent within the construction industry [63]. Lucas [17] utilized a product model and ontology to evaluate the data transference of FM information within a healthcare environment. Implementation of the product model and ontology allowed for the development of process models that evaluated the systems failures in HVAC equipment. Turkaslan-Bulbul [64] developed ontologies and a product model which provided computational support for a standardization of building commissioning procedures. The resultant product model standardized commissioning of air handling units and provided a data exchange framework for building commissioning information. Tsai et al. [65] presented an ontology-based framework that syndicates building intelligence. The framework provides a system that enriches BIM models with knowledge functions, enabling the system to automatically generate responses to facility issues. Park et al. [66], developed a construction knowledge retrieval systems using semantic tools to enable construction specific knowledge management. Others, such as Venugopal et al. [67] and Yang and Zhang [68], have utilized semantic interoperability and ontologies for model exchanges and the advancement of IFC.

In a few cases, researchers have evaluated safety using ontologies. Zhang et al. [69] recently presented an ontology-based sematic modeling system to capture construction safety knowledge. The ontology utilizes construction based safety information, such as the Occupational Safety and Health Administration (OSHA) regulation 1926 and the Occupational Injury and Illness Classification Manual, in an effort to enable more effective inquiry into construction site safety knowledge. Shansolketabi [63] evaluated safety within a facility management application by utilizing “chain of events” analysis to evaluate mechanical failures due to improper maintenance. Within the evaluation, an ontology was developed using cause-consequence chains to enable automatic generation of event sequences for a selected domain. The resultant cause-consequence model provided potential failures of a boiler system if proper maintenance was not executed.

3.3. The use of BIM for safety

In 1990 Hinze and Wiegand [70] surveyed 35 major U.S. design firms to evaluate their role in construction workers safety, subsequently laying the groundwork for the implementation of safety within BIM. During this time period, CAD was primarily used by designers during the design phase, therefore surveying major design firms in the United States was a natural starting point. The results showed that only a third of the respondents made any design decisions based on contractor's safety.

In 1997, in response to the studies performed by Hinze and Wiegand [70], Gambatese et al. [71] developed a computer program titled, "Design for Construction Safety Toolbox." The tool was intended to "assist designers in recognizing project-specific hazards and implementing the design suggestions into a project's design." This program was the first application of "Prevention through Design" [24]. Prevention through Design (PtD) is a concept of, "addressing occupational safety and health needs in the design process to prevent or minimize the work-related hazards and risks associated with the construction, manufacture, use, maintenance, and disposal of facilities, materials, and equipment" [72]. PtD in Europe and Australia, place the legal burden of safety on all parties involved in the project, not just the contractor as OSHA requires in the United States [22,73–75]. Research by Gambatese et al. [76] has shown that PtD can reduce the percentage of incidence that occur on a construction project; however, to date, the majority of PtD tools are primarily text based stand-alone checklists that often do not incorporate BIM [23].

Although PtD has been around for almost 20 years, the utilization of BIM applications for safety is a relatively new concept and the research in this field is in its infancy. Ku and Mills [23] state that using BIM to better address safety considerations via hazard recognition and design optimization could "create a built environment that successfully integrates safer construction processes." A thorough review of available trends and technologies is presented in Appendix 1, identifying applicable research in the "BIM for Safety" field, including the examples provided above.

3.4. Analysis of current trends and available technologies

As the FM industry continues to see incidence rates well over the national occupational average and an upward trend in fatalities, a fundamental shift in how safety information is disseminated and presented must take place. As the literature review has shown, a great deal of documentation has been produced in order to create a safe working environment for FM workers; however, this documentation only adds to the problem by creating even more sources of information requiring extensive reference prior to the start of an FM task. The incorporation of BIM into facilities management has attempted to improve where the documentation is stored and how it is presented but is rarely utilized due to "handover issues." Additionally, this information is rarely safety oriented, but instead is more asset and O&M based. Research being done to integrate BIM and safety has shown promise; however, a substantial amount of this research has been geared towards a safe working environment during the construction phase. As a result of the analysis conducted on current trends and technologies, the following summarizes the current challenges faced in each of the three areas of investigation.

Bureau of Labor Statistics data has shown, the upward trend of accidents within the field would indicate that FM workers are not executing tasks utilizing the appropriate safety information. This could be due to any combination of factors, including availability of information, safety culture, time constraints, or expertise. By adding convenience in obtaining information and simplifying the interface with which that data is presented, the likelihood of reference, retrieval, and execution will improve. This increased convenience will shorten the amount of time and effort an individual must spend in obtaining comprehensive safety information, expediting the reference timeframe and providing more time for the execution of the task. Additionally, simplifying the process should improve the worker's attitude towards referencing the safety information, thus positively shifting the culture.

Software advancements and research done in building information modeling in regards to facilities management has made immense steps within the last decade. The issues with data transference have been considered and continue to be addressed today. Although these systems are not seamless and the industry still experiences issues with data capture and transfer, through advancements in IFC, COBie, i-models, middleware, and research, the flow of information at the completion of a construction project into the FM phase is more streamlined than ever before. To date, much of this data management has focused on the flow of O&M information, construction as-builts, and asset management, with very few cases focusing on the identification and subsequent transfer of relevant safety information. By proactively establishing a protocol for safety, based on the equipment and environment present within the facility and structured within the BIM model, the information that is important to FM personnel can be obtained and presented independently in a BIM-based format, without the need to syphon through significant amounts of information.

Based on the information reviewed in the current market literature, analysis of the utilization of BIM for safety during the FM phase, shows none of the available literature reviewed has focused on the FM phase (see Appendix 1). However, analyses of the literature can help identify tools and techniques that could be expanded to consider the FM phase. By identifying what tools/techniques are being utilized and how those tools/techniques correlate to the hazards that this research attempts to mitigate, parallels to the framework that this research is developing can be made and potentially implemented within the system.

As a result of the analysis conducted on current literature, the following list summarizes the current challenges faced in each of the three areas of interest that the proposed framework attempts to address (Table 3).

4. Proposed framework

In an attempt to support worker's safety during the facility management phase, information obtained through the review of the three topics within Fig. 4 is utilized in order to develop a BIM-based framework to categorize, consolidate, process, and present job specific relevant safety information. By combining a data processing and rule based system with an interface, an FM worker can interact with a singular repository for safety information and receive necessary and concise safety instructions, eliminating the need to reference multiple resources in order to obtain comprehensive safety information timely. In this section the proposed framework is presented. Fig. 5 presents the basic framework design, with greater detail of each system identified in subsequent sections. Section 4.1 describes the methods utilized in order to develop appropriate safety attributes and protocols, as well as transfer that data from design and construction to the facility management phase. Section 4.2 reviews the data processing and rule based system (engine) that adds logic and guides the applicable safety data. Section 4.3 describes the characteristics of the safety protocol output and Section 4.4 summarizes the framework by providing an overview.

Table 3
Current challenges this research attempts to address.

Safety during facility management	Information is often fragmented creating inconvenience in obtaining comprehensive safety related information.
BIM for facility management	Handover/data transference issues are still prevalent. Handover information is rarely safety based.
BIM for safety	Research is heavily focused on the design and construction phase.

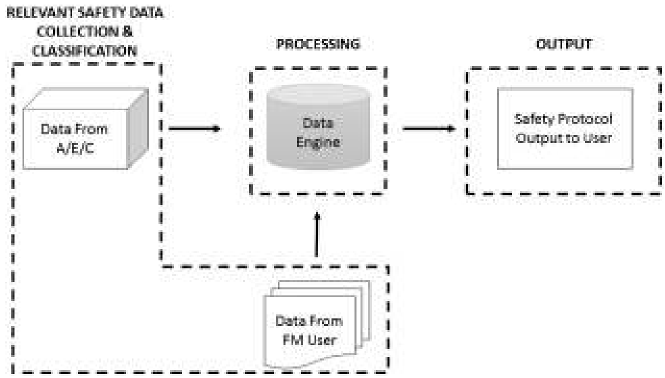

Fig. 5. Basic framework design.

4.1. Relevant safety data collection, classification, and transfer

In order for the proposed system to function, relevant safety information often encountered by FM staff during the repair and maintenance of a facility will need to be identified and organized. The following list presents the research design for obtaining, organizing, and structuring the applicable safety related information.

1. Develop a comprehensive list of safety attributes falling within the scope of this research (Fig. 6).
   a. A thorough review of safety documentation, NIOSH FACE reports, and data collection interviews (Type I) are utilized in order to obtain a comprehensive list of safety related properties relevant to FM workers.

2. Organize and classify safety related information (Fig. 6).
   a. Once identified, the relevant safety information is organized and classified using spreadsheets & mind-mapping.
   b. Type II interviews are utilized to validate the safety related properties and the classification of those properties.
   c. Organized and classified information allows for the development of property information that can be input into a comprehensive BIM Model. Defining these properties and identifying which contract entity is responsible for supplying the values for each property allows for the applicable safety related information to be input into the system.

3. Data transferred from various formats into a comprehensive model (Fig. 7).
   a. Categorized safety attributes and values are processed through various mechanisms, based on the applicable contract entities' existing infrastructure. The relevant safety information may come in the form of interoperable models, non-compatible models, documents, and other formats.
   b. In order to place all of this information into a comprehensive model, a number of IT Tools for data management and model integration are utilized.
   c. Once comprehensive relevant safety information is available within the BIM model, a strategic export of applicable information is exported to prepare for input into the data engine.

4.2. Data engine

A data processing and rule based system (DPRBS) is used to add logic and guide the information exchange in order to provide applicable and necessary information to FM staff in a timely manner. Based on the values assigned to the attributes, rules and process models guide the information logic and present the information via a graphical user interface (interface). The interface is developed to produce applicable safety protocols based on two factors:

a. The information present in the asset selected, known as a "Direct Command."
b. The responses given by the user to a series of questions that the GUI is programmed to ask, known as a "Launch System."

The following is an example of the data engine functionality, utilizing a single safety attribute, "MaxMaintenanceElevationInFeet." This attribute has been identified to provide FM workers with three pieces of information.

1. The maximum repair and maintenance elevation (in feet) of the specific asset.
2. If the asset requiring maintenance utilizes a lift system (ladder, aerial lift, etc.) for repairs.
3. If the asset requiring maintenance utilizes a fall arrest system due to elevation or positioning.

Based on the elevation in 1, the system will query the user on 2 & 3. If the value in 1 is less than an elevation deemed safe without the need for a lift system/fall arrest system, the DPRBS will not launch the query system (2 & 3). The system functionality is presented schematically in Fig. 8.

In the above basic example, the MaxMaintenanceElevationInFeet is input as 12 ft. Due to this height, the system initiated the query system, asking the FM worker which lift system will be utilized and if the positioning of the asset requires the use of a fall arrest system. The query

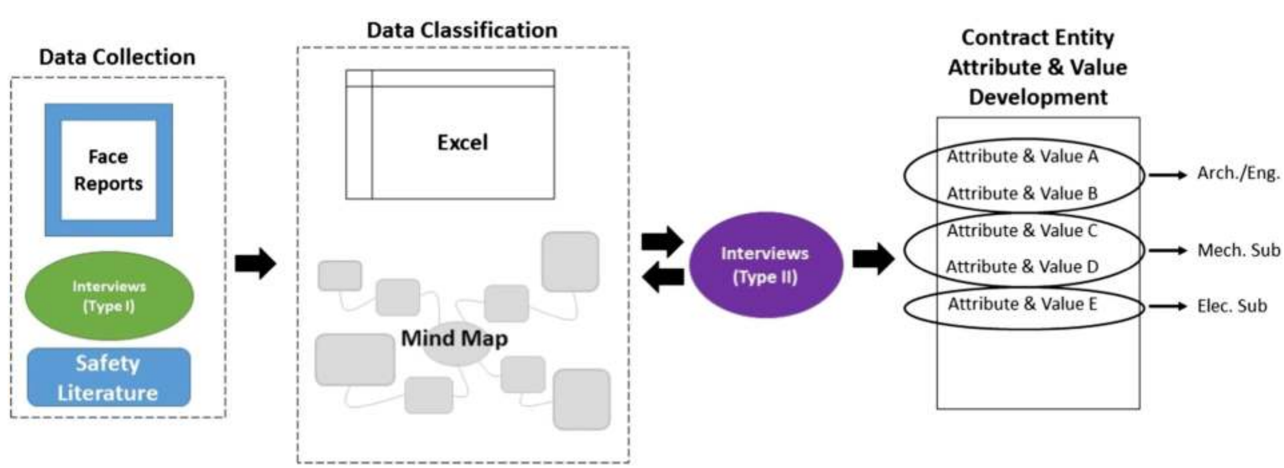

Fig. 6. Data collection and classification.

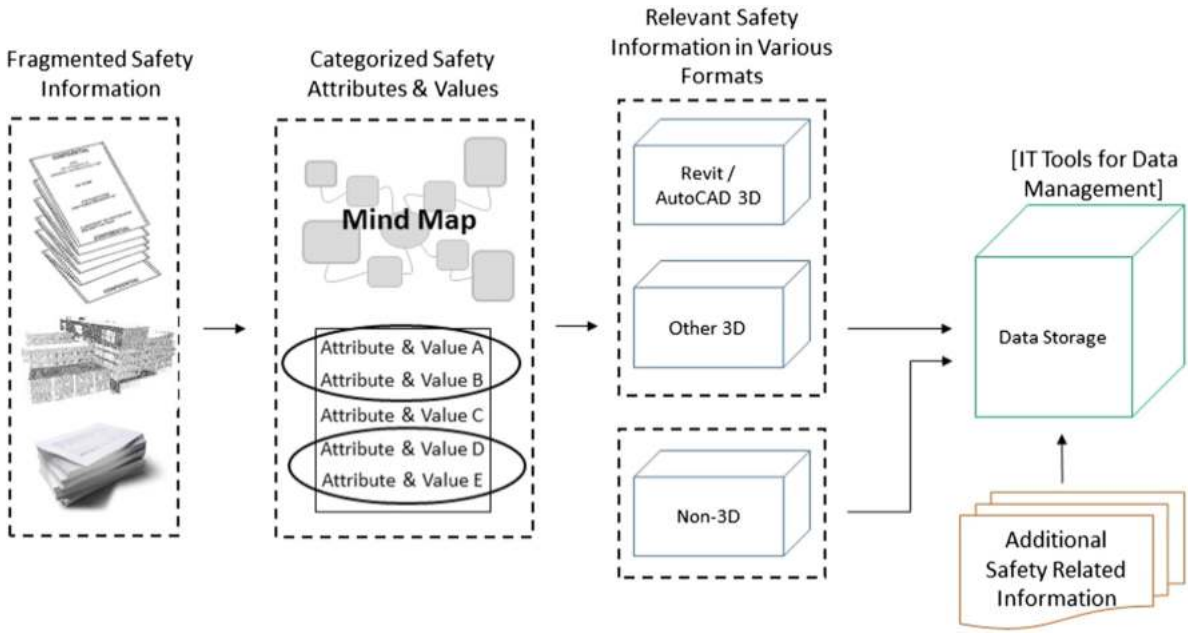

Fig. 7. Attribute data transfer.

system is utilized to provide task specific protocols based on the approach that the worker intends on taking and requires the FM worker to proactively consider the systems that the task requires. Based on the elevation value and the FM worker responses, a task specific safety protocol is issued. The "Direct Command" and "Launch System" functionality is utilized for all predefined safety attributes.

4.3. Safety protocol output to user

The output of the information plays an important role in any virtual system. A useable interface must maintain a number of characteristics in order to allow for all levels computer competency to interact with the system as intended and the output must be easy to understand and concise. Although this research focuses primarily on the data and the data processing, future research could utilize prototypes to test the accessibility of the data output. Characteristically, the interface and output must be comprehensive, task-specific, and easy to utilize, as a deviation from this would undermine the requirement to deliver information timely. Additionally, the output could utilize a number of media (i.e. text, pictures, videos, and augmented reality) and technologies (RFID and barcode).

4.4. Schematic framework summary

Fig. 9 presents the complete framework for the research. Throughout the lifecycle of the project, relevant safety attributes are given values by the various contract entities responsible for those assets from, what would otherwise be fragmented safety information. Through various data transfer mechanisms, based on the type and format of the safety attribute submissions, the relevant safety information is placed into a data storage repository. Utilizing process flows and existing IT tools for data management, such as DataTools, Navistools, and iConstruct the correct information can be stored in a similar format. In addition, relevant safety information provided by the owner of the facility can be input into the system to meet organization specific requirements.

In order to retrieve task specific safety information, the user will launch the DPRBS and select the asset requiring maintenance. Based on the values already in place for that particular asset, two background activities will take place. First, relevant safety applicable information

Direct Command

FM Safety Attributes	*Input Value*	*Background*	*System Launch*
MaxMaintenanceElevationInFeet	***12***	INITIATE LIFT SYSTEM QUERY & FALL ARREST QUERY	LAUNCH LIFT SYSTEM & FALL ARREST PROTOCOL

Launch Systems

Launched System	*Query*	*Selection*	*FM Worker Selection Protocols*
LIFT SYSTEM	SELECT: LADDER / AERIAL LIFT / SAFETY PLATFORM / SCAFFOLDING / NA	**radio button selection**	OUTPUT FM WORKER SELECTION PROTOCOLS
FALL ARREST	DOES ASSET ELEVATION / POSITION REQUIRE A FALL ARREST SYSTEM?	**YES / NO**	If Yes: OUTPUT FALL ARREST SYSTEM PROCEDURES

Safety Protocol Output
OUTPUT **MaxMaintenanceElevationInFeet** & **FM WORKER SELECTION PROTOCOLS**

Fig. 8. Example of DPRBS functionality.

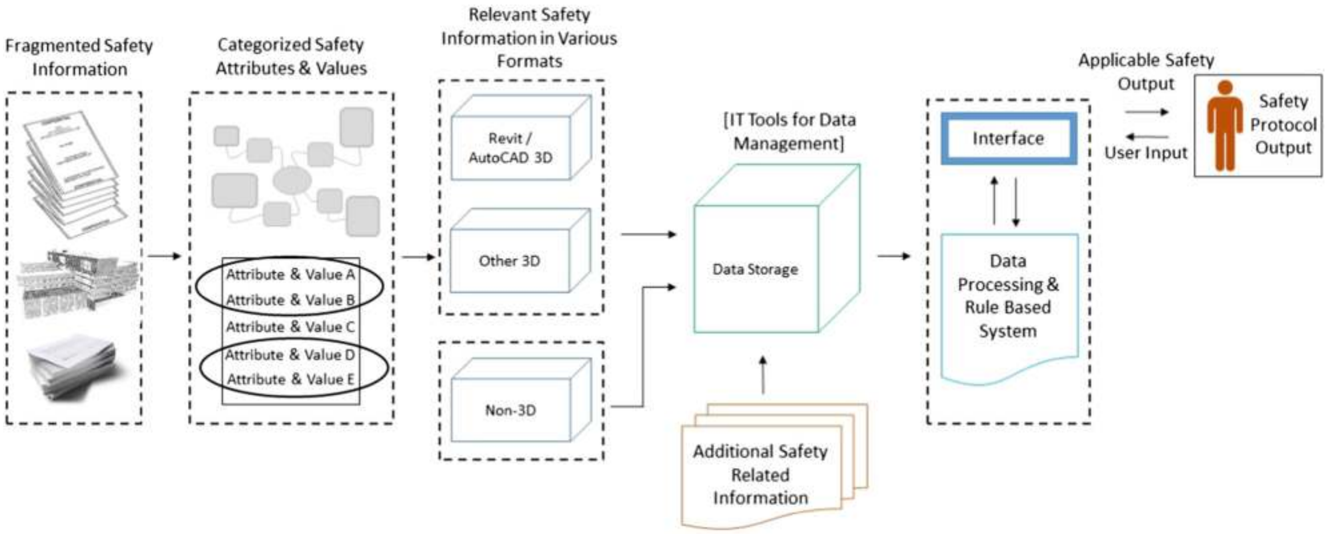

Fig. 9. Proposed framework.

will be sent to the end user interface for finalized safety protocol reference. Second, the interface will ask the user a series of short questions in order to develop a task specific protocol based on the asset being serviced, environment, and circumstance. Utilizing a question based system urges the worker to proactively consider the safety plan prior to the execution of the task, similar to the tactics used in inquiry-based learning. Based on the asset selected and the responses by the user, a safety protocol output will be delivered to the FM worker.

5. Conclusion and discussion

As shown in this document, personnel in the field of FM are susceptible to work related injuries, illnesses, and fatalities. In an industry that often requires repair and maintenance activities to be completed in an expeditious manner, the time and effort in obtaining information needs to be efficient. The coordination of safety related information and the storing of this information presents a fragmented system that suffers from disorganization and improper identification, creating inefficiencies in the obtaining of comprehensive safety related information. The current inconvenience created within the system can cause FM personnel to bypass the referencing of safety information, increasing the likelihood of work related injuries, illnesses, and fatalities. By organizing relevant safety information and providing a more convenient method for obtaining this comprehensive information, the likelihood of reference will improve, mitigating some of the risks associated with FM activities.

The proposed framework attempts to support safety during the facility management phase through a number of research contributions. These contributions are as follows:

- Identification and classification of FM relevant safety attributes.
- Identify the data flow of classified attributes from inception to the data processing and rule based system (DPRBS).
- Develop a DPRBS to consolidate and process the classified attributes.

Upon execution of the framework, a pilot study could be utilized to test the functionality of the system and determine the usefulness of the system prior to full development. This would require development and implementation on an industry partner's system. A fully developed system would provide FM workers the ability to interact with a single GUI to obtain a comprehensive safety protocol specific to a required task. This would improve worker safety, efficiency, and knowledge transfer of information.

Table 4
Categorization of area of research and percentage of each category.

Area of research (AoR)	Percent of literature
All (8)	50%
Falls only (5)	31%
Other (2)	13%
Falls and hazardous environments (1)	6%

Table 5
Categorization of BIM technology and percentage of each category.

BIM technology	Percent of literature
BIM 4D (7)	30%
Rules algorithm (7)	30%
BIM design (3)	13%
Design for safety (3)	13%
Virtual reality (3)	13%

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Appendix A

The table is being utilized to organize the BIM for Safety research into the following categories:

- Phase — The portion of the building lifecycle the research is addressing.
- Area of Research — The correlation between the three hazard categories that this research addresses (falls, contact with/struck by, and hazardous environments) and the research being presented in the table.
  - Other — Denotes a non-specific categorization.
  - All — Identifies research that addresses all three categories.

Appendix 1
BIM for safety research.

Phase	Area of research (AoR)	BIM technology	Summary	Title	Author
Design	All	Design for safety	Survey identifying the designers role in construction safety	Role of designers in construction worker safety	Hinze and Wiegand [70]
Design	All	Design for safety	400 + design suggestions that alert a designer when a project-specific safety hazard is identified	Tool to design for construction worker safety	Gambatese et al. [71]
Construction	All	Virtual reality	A database of safety processes is incorporated into a “virtually real project” to allow for a walkthrough to identify safety hazards and select accident prevention	Integration of virtually real construction model and design-for-safety process database	Hadikusumo and Rowlinson [77]
Design	All	Design for safety	A theoretical basis developed to provide a tool that architects, engineers, construction managers (CMs) and specialty contractors can use to estimate the time, cost, and worker safety impacts of specific design and construction process alternatives for their projects	The link between design and process: dynamic process simulation models of construction activities	Slaughter [78]
Not applicable	Other	Virtual reality	Using virtual reality for hazard identification training in mining operations	Implementation and evaluation of a VR task-based training tool for conveyor belt safety training	Lucas and Thabet [79]
Construction	Fall hazards	BIM 4D	Uses 4D for site organization to promote safety against falls	BIM-based site layout and safety planning	Sulankivi et al. [80]
Construction	All	BIM 4D/rules algorithm	A conceptual model that enables forecasting of safety risks in projects for different trades. Uses a knowledge base of construction activities and probabilities of loss-of-control events, coupled with a project's construction plan and a digital building model, to forecast risk levels for work teams	‘CHASTE’: construction hazard assessment with spatial and temporal exposure	Rozenfeld et al. [81]
Construction	Fall hazards	BIM 4D/rules algorithm	A rule based system that analyzes design information to automatically detect working-at-height hazards	An integrated safety management with construction management using 4D CAD mode	Benjaoran and Bhokha [82]
Not applicable	Other	BIM Design	Uses computer image generation for job simulation (CIGJS) to review potential safety hazards in occupational settings. This is not specifically geared towards construction, but could be utilized as such	Computer image generation for job simulation: an effective approach to occupational risk analysis	Patucco et al. [83]
Construction	Falls & hazardous environments	BIM 4D/rules algorithm	1) Uses safety codes to automatically generate Dynamic Virtual Fences (DVF) for collision prevention & fall protection 2) Uses Real-Time Location Systems (RTLS) for worker tracking to provide warnings when approaching hazardous areas	Automatic generation of dynamic virtual fences as part of BIM-based prevention program for construction safety	Hammad et al. [84]
Design and construction	All	Virtual reality/BIM 4D	Explores relationships between construction safety and digital design practices with the aim of fostering and directing further research. It surveys state-of-the-art research on databases, virtual reality, geographic information systems, 4D CAD, building information modeling and sensing technologies	Construction safety and digital design: a review	Zhou et al. [85]
Construction	Fall hazards	Rules algorithm/BIM 4D	Fall hazard safety issues unknowingly built into a construction schedule can be identified by utilizing Automated Safety Checking in a 4D simulation application	Utilization of BIM-based automated safety checking in construction planning	Sulankivi et al. [86]
Design	Fall hazards	BIM design/rules algorithm	Algorithms that automatically analyze a building model to detect safety hazards and suggest preventive measures to users are developed for different cases involving fall related hazards	Building Information Modeling (BIM) and safety: automatic safety checking of construction models and schedules	Zhang et al. [87]
Construction	All	Rules algorithm	Utilizes construction based safety information, such as the Occupational Safety and Health Administration (OSHA) regulation 1926 and the Occupational Injury and Illness Classification Manual, in an effort to enable more effective inquiry into construction site safety knowledge through the use of an ontology	Ontology-based semantic modeling of safety management knowledge	Zhang et al. [69]
Construction	All	Rules algorithm	Identifies focal points of occupational accidents as well as risks and hazards influencing the safety of construction workers and determines the job hazards related to construction process. After linking such risks to a 3D building model, the results are demonstrated with the commercial BIM software ceapoint desiteMD	Model-based construction work analysis considering process-related hazards	Melzner et al. [88]
Construction	Fall hazards	BIM design/BIM 4D	Investigated the effectiveness of BIM technologies in developing, communicating and implementing a construction site safety plan. Four-dimensional (4D) phasing simulations, 3D walk-throughs and 3D renderings were utilized for identifying hazards and communicating safety management plan to the workers	A BIM-based approach for communicating and implementing a construction site safety plan	Azhar and Behringer [89]

- BIM Technology — The modeling tools or techniques used in order to achieve the research objective.
  - BIM Design — Requires additional design to implement safety feature (i.e. scaffolding, fencing, etc.)
  - BIM 4D — Utilizes 4D technologies (3D model & Schedule)
  - Rules Algorithm — Utilizes a rule based system to output safety information
  - Virtual Reality — Uses VR to visualize a work environment or process
  - Design for Safety — Technique uses to forecast safety hazards using a BIM model.

BIM for safety in this research only refers to safety to humans and does not address safety of materials (e.g. structural integrity) or life-safety systems (fire safety).

The following tables present the "Area of Research (AoR)" and "BIM Technology" usage within Appendix 1. Table 4 presents the categories identified under "Area of Research" and the ratio to the total percentage of each area, while Table 5 does the same with "BIM Technology."

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