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Knowledge-assisted BIM-based visual analytics for failure root cause detection in facilities management

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ABSTRACT

Facilities managers need to identify failure cause–effect patterns in order to prepare corrective and preventive maintenance plans. This task is difficult because of the complex interaction and interdependencies between different building components. Standardization based on Building Information Modeling (BIM) provides new opportunities to improve the efficiency of facilities management (FM) operations by sharing and exchanging building information between different applications throughout the lifecycle of the facilities. This paper aims to utilize BIM visualization capabilities to provide FM technicians with visualizations that allow them to utilize their cognitive and perceptual reasoning for problem solving. It investigates a knowledge-assisted BIM-based visual analytics approach for failure root-cause detection in FM. For this purpose, the inspection and maintenance data of Computerized Maintenance Management System (CMMS) are integrated with a BIM. Moreover, various sources of building knowledge such as fault trees and relationships between components are formally represented. These resources are used to create custom visualizations through an interactive user interface which helps in exploiting the heuristic problem solving ability of field experts to find root causes of failures in a building.

1. Introduction

Decisions on maintenance-related tasks are usually made based on various types of accumulated historical data, such as design drawings, inspection records, and sensing data [9]. Most of these data are text-based, which makes the process of correlating the information time-consuming and less intuitive. In the current state of practice, facilities management (FM) technicians add inspection and maintenance data to the database of a Computerized Maintenance Management System (CMMS). The CMMS application provides managers and technicians with various reports related to maintenance and repair issues. However, discovering the root cause of a problem based only on the data in a CMMS is difficult. This is due to the complexity of the interrelations between the various building components and systems [1], the multiplicity of building components and various changing environmental factors. Finding the root causes of failures can be facilitated by providing the FM technicians with deductive models that systematically document the possible root causes of failures. These models are developed based on experts' knowledge of various trades. Additionally, the complex relationships between building elements can be captured in a building model to associate the generic failure causes to specific building elements. Finally, the results can be visualized to present the information (such as the condition of the assets), to be used for exploring the spatial distribution of failure root causes, and to infer failure patterns.

One technology that can facilitate the above tasks is the Building Information Modeling (BIM). BIM is emerging as a method for creating, sharing, exchanging and managing information throughout the lifecycle of a building between all the stakeholders [19]. BIM has the potential to help improve the quality of FM by visualizing the large amount of lifecycle data. The Industry Foundation Classes (IFC) is an object-oriented, non-proprietary building data model that has matured as a standard BIM for facilitating interoperability [19]. In addition, the Construction-Operation Building Information Exchange (COBIE) standard provides facilities managers with some of the required data for Operation & Maintenance (O&M) and for project handover [11].

On the other hand, knowledge-assisted visualization, which integrates and utilizes domain knowledge to produce effective data visualization, has been a fast growing field [33]. Visual analytics (VA) combines automated analysis techniques with interactive visualizations for an effective understanding, reasoning and decision making on the basis of very large and complex datasets using the visual perception and analysis

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capabilities of the human user [21,23]. VA provides the experts with the insights and reasoning artifacts that make them more capable of performing complex analytical processes [33]. VA can apply the expert cognitive capabilities and judgment for the following scenarios: (1) visualizing possible causes of a certain problem based on available lifecycle knowledge and the relationships between elements in a BIM. The visualization of all known possible causes provides the opportunity for heuristic problem solving to find the main cause of the detected problem; (2) analyzing the temporal and spatial distribution of problems to infer patterns and trends by visualizing this distribution and the occurrence frequency of the problems in the past and present situations; and (3) visualizing the chain of effects caused by changing the status/condition of a certain component (e.g., failure or temporary shutdown of a mechanical component) in order to simulate the resulting effects using the relationships between assets. This scenario can be used to plan for redundancy, to help in developing incident management plans, and to prepare tasks related to change management plans.

The present paper investigates the potential of knowledge-assisted BIM-based VA for visualizing the possible root causes of failures. In this research, BIM is considered as the primary data source for information related to building lifecycle. BIM data should be also linked to data stored in FM software applications (e.g., Computer Aided Facilities Management (CAFM), Enterprise Asset Management (EAM), and CMMS). Additionally, various types of building knowledge, such as fault trees and the relationships between components, are formally captured and used for creating visualizations. The objectives of this paper are: (1) to investigate the potential of knowledge-assisted BIM-based VA for the failure root-cause detection scenario; (2) to identify the resources available in the IFC for the purpose of VA; (3) to identify the steps to apply FM visual analytics; and (4) to demonstrate the applicability of the method using a case study.

2. Literature review

2.1. Facilities lifecycle management using BIM

CAFM [34] and CMMS [30] are essential tools for managing facilities during the O&M phase. However, these systems do not contain all the necessary O&M data and are often not interoperable with other software applications. Owners and operators can use the high-quality building information from a BIM during the O&M phase of the building's lifecycle [28]. Becerik-Gerber et al. [7] performed interviews with FM personnel to identify the role of BIM in FM. Their study shows that most of the current FM functions are done manually and that using BIM in FM can decrease the chances of errors and increase efficiency.

In order to extend BIM to include FM data, Hassanain et al. [14] proposed an IFC-based data model for integrated maintenance management for roofing systems. Later on, Hassanain et al. [15] presented a general object-oriented schema for asset maintenance management that supports information exchange among different domain areas. However, the BIM visualization potential for improving maintenance activities was not considered in their study.

To utilize the potential of BIM for FM, a case study has been performed for BIM modeling of Sydney Opera House (SOH) [29] in which information about the service, maintenance, cost, and data fields for *Building condition indices* were added to the model. Visual reporting was provided using queries based on these attributes in the BIM and color coding techniques [8,29]. However, the relationships between assets and the knowledge related to failure causes were not included in this study.

2.2. Building knowledge sources

2.2.1. Asset/system hierarchies, system modeling and operational procedures

An asset hierarchy is used to classify and cluster building components in different categories which can reflect similar characteristics (e.g., materials) or similar inspection needs [1,31]. Additionally, the IFC schema provides a logical hierarchy of building elements through the definitions of various domains [18]. Moreover, there are various standard techniques to formally model building systems and the interaction between their components (e.g., Petri-Nets and SysML) [5]. Operation manuals for assets and systems which contain procedures such as start-up/shut down, maintenance/repair, and safety are other sources of building operation knowledge that are provided by manufacturers or developed internally. These sources of knowledge can be utilized for the purpose of creating visualizations. The asset hierarchies and system models can be used to identify relationships between assets that can be used for finding failure root causes and creating customized visualizations.

2.2.2. FM expert systems

Expert systems are knowledge-based decision-support systems with a heuristic component that use knowledge to make recommendations, draw conclusions, and/or propose a hypothesis [20]. Chen et al. [10] reviewed several studies on the development of expert systems and concluded that, for building facilities, the predictive method based on maintenance data has not yet been studied. Moreover, they concluded that the reviewed expert systems generally provide text-based forms and 2D graphical user interfaces for receiving users' inputs and presenting analytical results. They developed an expert system which utilizes visualization, databases, reliability, and optimization technologies to provide predictive information based on accumulated FM data to facilitate decision making. They used OpenGL [27] to create a 3D model as the interface for accessing various maintenance data. However their method did not use BIM data to support failure analysis.

2.2.3. Condition Assessment Systems (CASs)

Condition assessment is the basis for determining the level of preventive maintenance needed for building's systems and components [36]. Ahluwalia [1] and Amani and Hosseinpour [4] listed various definitions presented in the literature and current CASs for buildings. Some of the reviewed CASs utilize various reliability/serviceability analysis methods including deterioration modeling to estimate the condition of assets. For example, Myrefelt [26] provided a study on the reliability and functional availability of Heating, Ventilation, and Air Conditioning (HVAC) systems that includes mathematical modeling together with empirical results. The CASs' data are used in our method for color coding of assets based on their condition values.

2.2.4. Fault/failure modeling

Deductive fault models are used to deduce the causes of an undesired event by identifying events and modeling their causes. Fault tree analysis (FTA) is a graphical tool for analyzing possible causes of a failure. It can be used as a prevention tool or as a diagnostic tool. A fault tree is constructed to model the logical relationships of events and to provide a framework for qualitative and quantitative evaluation of the undesired events. An FTA exhaustively identifies the causes of failure and prioritizes the contributors to this failure. Using the data about the probabilities of the causes, the probability of system failure can be determined [32].

Hessian et al. [16] used FTA to model failure modes of an HVAC system control room of a large production facility. They analyzed various failure combinations that could cause system failure in order to enhance system availability through design and/or procedural modifications. Wong [35] collected time-to-failure and failure modes data for the HVAC of large buildings over a period of six years to quantify the reliability of the system using fault trees. Khan and Haddara [22] proposed a method for risk-based inspection and maintenance. Probabilistic failure analysis was conducted for HVAC systems using FTA together with components' failure data and human reliability data for the determination of the frequency of occurrence of an accident.