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A system framework for RCM-based facility maintenance management in a park area

Yuan Ren[a], Zhiliang Ma[a,*], Xuefeng Song[b]

[a]Tsinghua University, Qinghuayuan 1 Haididan District, Beijing 100084, China
[a]Zhongxuanzhiwei Tech., Zhongfuligong Fengtai District, Beijing 100084, China

Abstract

There is an increasing number of university campuses and science parks in China. The park areas usually have only one owner, but many organizations, for example, departments and companies, engaged in the facility maintenance management (FMM). These organizations usually are responsible for different disciplines in different facilities independently. Considering the fact that facilities influence each other most of the time, FMM performance for the entire area is thus unwarrantable. Therefore, we proposed a system framework for FMM in a park area based on Reliability-Centered Maintenance (RCM) and the integrated use of Geographic Information System (GIS) and Building Information Modeling (BIM). The requirement analysis was carried out and the system framework was designed. The system framework is valuable for developing software systems that can support multiple FMM organizations in an area to work on the same platform, avoid management problems and achieve better performance. A software system based on the proposed framework is now under construction.

Keywords: FMM ; Framework design; RCM; BIM; GIS;

1. Introduction

With the rapid development of education, science and technology in China, there is an increasing number of university campuses and science parks. They are a kind of estate, which is totally called a park area, and has multiple facilities but only one single owner. A park area usually covers a large consistent area where both horizontally distributed facilities, such as pipelines, and vertically distributed facilities, such as buildings, are located. Due to the diverse types of the facilities and different maintenance requirements from them, a park area is usually assigned to multiple organizations, for examples, departments and companies, for facilities maintenance management (FMM). The organizations are under the supervision of the administration of the park area but work independently by different disciplines in different facilities.

FMM in a park area is not just a summation of FMM in each single facility. From a physical point of view, it needs to take the interrelationships between facilities, and between facilities and their surrounding environment into consideration to identify all potential risks. From an organizational point of view, it needs to coordinate the divisions of work between multiple organizations to avoid overlapped or missed maintenance responsibilities. Without a dedicated information system, FMM in a park area usually involves two typical problems. First, for FMM organizations, they work independently without sharing information with each other so that it is likely to cause construction accidents. For example, Department A changes the depth of a natural gas pipeline in an emergency repair but tells no other departments. Later on when Department B does an excavation at the same place, there will be a high

Corresponding author: Zhiliang Ma email: mazl@tsinghua.edu.cn

risk of leak accident because B has no awareness of the change of the pipeline. Second, for the administration of the park area, it is hard to guarantee maintenance reliability and cost-effectiveness of the entire area. This is because FMM managers usually work on their own, which may result in different levels of maintenance performance, whereas some could be very poor. Considering that facilities influence each other, maintenance reliability and cost-effectiveness of the entire area is unwarrantable in this way.

In Architecture, Engineering, Construction, Facility Management (AEC/FM) industries, Computerized Maintenance Management Systems (CMMS) have been deployed for (1) service request generation, (2) work order management, (3) required/used work resources calculation/tracking, (4) employees record management, and (5) inventory control [1]. Maintenance staff can use CMMS to upload and share maintenance information, such as drawings, documents and maintenance logs to ensure good information interoperability among the stakeholders. Nevertheless, there is still no CMMS applicable for FMM in a park area up to now.

Reliability-Centered Maintenance (RCM) is a systematic approach to evaluate a facility's equipment and resources to best mate them to obtain a high degree of facility reliability and cost-effectiveness [4]. RCM has been widely applied in military, nuclear energy, electric power, aviation, aerospace, shipbuilding industries [5], and some trials in residential buildings [7], historical buildings [8] and hospital facilities [9] have been conducted in AEC/FM domains. Nevertheless, how to apply RCM in FMM in a park area for maintenance optimization is still a problem to be solved.

The objective of this study is to propose a system framework for FMM in a park area based on RCM and the integrated use of GIS and BIM. This paper first reviews the literature of existing commercial systems and academic researches related to FMM and analyzes their applicability for the park area, then conducts the requirement analysis of the system. Finally the system framework is designed based on the integrated use of GIS and BIM and RCM method.

2. Literature review

2.1. Commercial system solutions

In AEC/FM, typical CMMS for FMM (FMM system hereafter for short) include FM:Interact [10], ARCHIBUS [11], AiM Facility Management [12], Maximo [13]. In recent years, commercial CMMS software has integrated technologies such as Construction Operations Building Information Exchange (COBie), Geographic Information System (GIS) and Building Information Modeling (BIM) for auto-generation of property and asset records, macro-level graphic visualization, work order mapping, bi-directional data exchange with BIM models [14]. However, existing commercial systems are hardly applicable in a park area for three reasons. First, they seldom provide automated analysis tools for maintenance planning and optimization, which multiplies the need for facility managers and professionals. Second, they do not support visualization of the entire park area in 3D graphics, which makes it hard to analyze the interrelationships between facilities, and between facilities and their surrounding environment. Third, they are designed for the case where the responsibilities for facility maintenance are taken by a single organization. If all FMM organizations in a park area work on this kind of system together, an organization will see or even be able to edit the business data of all the organizations, which is not safe. Therefore, existing commercial systems have limitations in the application for FMM in a park area.

2.2. Related academic researches

Currently there is no research reported about FMM system in a park area with multiple FMM organizations. Previous researches on FMM system can be divided into two categories, researches that realized the visualization of facility maintenance information, and researches that not only realized visualization but also business functions to support maintenance work flow, collaboration of multiple disciplines and optimization of decision-making. It is necessary to clarify that some researches used the term FM (Facility Management) but not FMM because they studied systems for general FM where FMM functions are included.

Regarding the visualization of facility maintenance information, Kang [17] developed a prototype system that could present related facility property data in the user's perspective based on the effective integration of BIM, GIS and FM data. Hu [18] realized a system that used a composite multi-scale BIM model to improve the 3D display efficiency in the operation and maintenance of mechanical, electrical and plumbing (MEP) projects. These researches improved information acquisition efficiency for maintenance staff.

Regarding the integration with maintenance work flow, Lin [19] proposed a mobile- and BIM-based FMM system which could provide easy access to basic maintenance information and maintenance records, generate maintenance

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forms for facility status updating, display facility status in 3D graphics and generate work reports automatically. Parsanezhad [3] devised a BIM-based integrated information web system that has functions for maintenance request send-receive. Xiao [20] proposed a mobile application framework of the BIM-based FM system under a cross-platform structure for on-site maintenance staff to query facility information and upload maintenance log. These researches improved the efficiency of maintenance staff.

Regarding the collaboration of multiple disciplines, Lee [21] implemented a web-based BIM interactive collaboration system for FM where users of multiple disciplines such as designers, FM managers and on-site staff can find required information, initiate a discussion and issue or arrange operation and maintenance tasks. The mobile app implemented by Xiao [20] could also support FM managers and on-site staff work in a unique platform. These researches helped maintenance staff achieve good information interoperability and timeliness.

Regarding the optimization of decision-making in FM, Hao [22] proposed a decision support system for FM that is intended to integrate and balance the employment proportion of different maintenance strategies to obtain a full-scale optimal maintenance program. Shen [23] proposed an agent-based, service-oriented conceptual framework that provided life-cycle information for decision making in facility operation and maintenance. Cheng [24] presented a decision support system framework based on BIM that utilized information from FM records to assess the condition of facilities, predict potential failure and develop optimized maintenance and budget allocation plans. In a BIM-based system framework, Chen [25] realized the automatic scheduling of work orders for facility maintenance. These researches helped improving the efficiency of decision-making, avoiding risk of catastrophic failure and reducing cost.

Although the research systems are powerful enhancement to solve many practical problems, they cannot be applied directly in a park area, due to similar reasons as stated for the commercial system solutions.

3. Requirement analysis of the FMM system for a park area

3.1. User analysis

In order to identify typical users and their requirements for the system, field investigations were carried out in Tsinghua University, BeiHang University and Lize Financial Business District of Beijing, in Beijing, China. They are all typical park areas. The field investigations includes two parts. First, interviewing with maintenance staff and managers. Second, collecting business documents, such as organization diagrams or maintenance forms.

The FMM in a park area runs on the collaboration of different functional departments and property management companies, whose managers and members are supposed to be the users of the system. The functional departments and property management companies, the relationships of them and the typical role settings in them are described by a three-layer organization diagram like Fig 1.

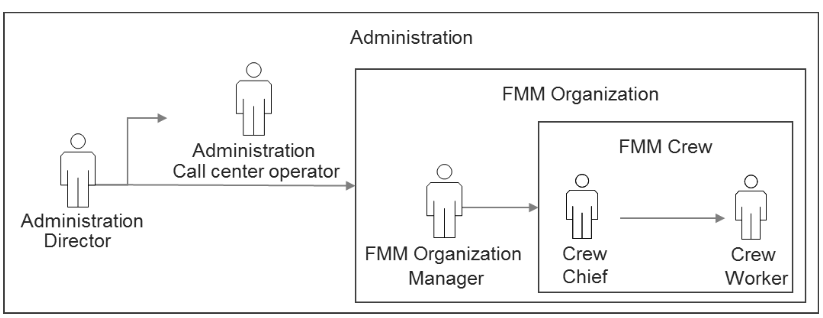

Fig. 1. Organization diagram of FMM in a park area.

The outermost layer of the diagram is the administration layer. Administration is on behalf of the owner of the park area to take charge of the overall FMM. There is only one administration in a park area. In this layer, there are two roles, i.e., the director and the call center operator. The former supervises the FMM performance in the park area and makes decisions on important issues. The latter collects and transfers service requests to the corresponding FMM organizations.

The next layer inside the administration layer is the FMM organization layer. FMM organization is the independent organization in charge of the FMM of certain facilities. There are many FMM organizations in a park area, in which there are FMM managers to do jobs like making maintenance plans and tracking the progress of maintenance tasks.

FMM organizations usually have their own crews to execute maintenance tasks, which are represented by the innermost layer of the diagram. A FMM organization could have more than one crew for different types of facilities, like electricity issues crew for power supply facilities and water issues crew for water supply facilities. In the crew, there are workers and a chief, where the chief is responsible for each task and workers take orders from him.

Arrows in the diagram represent a relationship of leadership. Generally speaking, crew workers receive orders from crew chief. The FMM crew receives tasks from managers in the same FMM organization and need to report to them. The FMM organizations are under the supervision of the director from the administration, where the call center operator also need to report to the director.

3.2. Functional requirement analysis

The functional requirements for the system come from each user's business processes of FMM and the needs to solve the existing problems, namely, the need to solve the information sharing problem and the need to apply RCM for maintenance optimization. As shown in Table 1, functional requirements from different users are summarized and divided into two categories, visualization functional requirements and business functional requirements.

Table 1. Function requirements from different users.

User	Layer	Visualization Functional requirements	Business Functional requirements
Director	Administration	3D browsing of the park area.	Maintenance plan approval; Maintenance performance assessment.
Call center operator	Administration	3D browsing of the park area; 3D browsing of facilities.	Repair task assignment.
Manager	FMM organization	3D browsing of the park area; 3D browsing of facilities.	RCM-based paintenance plan optimization; Maintenance plan creating; Maintenance task assignment; Task status tracking; Task result confirming.
Chief	FMM Crew	3D browsing of facilities.	Task result confirming.
Worker	FMM Crew	3D browsing of facilities.	Task result reporting.

Take the user manager from FMM organization as an example. A manager's duty in FMM is to create maintenance plans, assign maintenance tasks to workers, track the status of on-going maintenance tasks and confirm the results of finished tasks. When creating maintenance plans, as analyzed before, the manager should perform optimization analysis based on RCM. Thus, for the business functions, the manager requires the system to support RCM-based maintenance plan optimization, maintenance plan creating, maintenance task assignment, task status tracking and task result confirming. In addition, since facilities influence each other in a park area, the manager need not only focus on the facilities but also analyze the interrelationships between facilities, and between facilities and the surrounding environment, so the manager should require the system to support both 3D browsing of facilities and 3D browsing of the park area.

4. Framework design of the FMM system for a park area

4.1. FMM information model

Based on a detailed investigation of FMM in Tsinghua University, an information model is developed using the method proposed by Yu [26]. In this model, each entity represents real world objects, physical or conceptual, for the FMM in a park area.

As Fig 2 shows, the physical hierarchy of a park area is represented by four entities: 'Park', 'Unit', 'Facility' and 'Component'. The entity 'Park' refers to the type of estate that covers a large consistent area while the entity 'Unit' refers to each construction object whose functions are self-contained in the park area. A 'Unit' entity can consists of several 'Facility' entities. The entity 'Component' represents a functionally independent part in the 'Facility' entity. For example, in the case of Tsinghua University, the university campus is represented by a 'Park' entity while the laboratories and libraries are represented by 'Unit' entities. A library is facilitated by several buildings and maybe a parking lot, which are represented by 'Facility' entities. In the library, object such as a door, an air conditioner or a valve of a water supply pipeline is represented by the 'Component' entity.

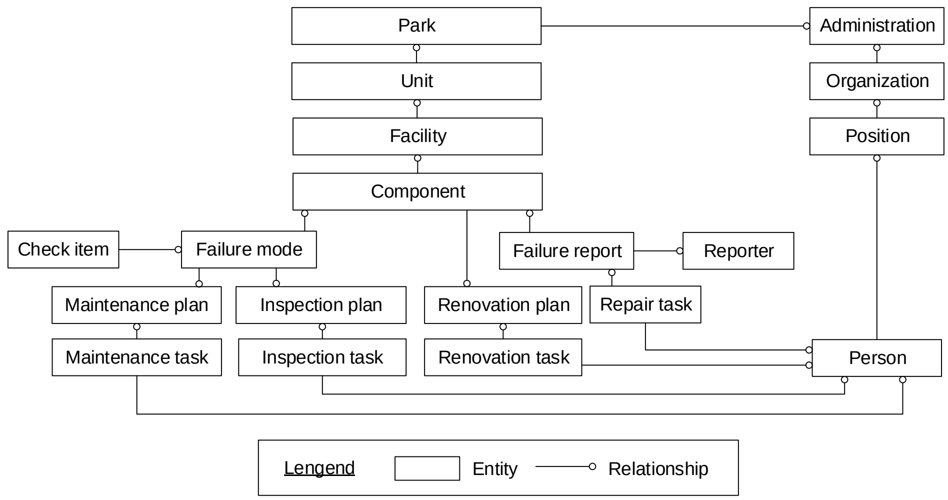

Fig. 2. Information model of FMM in a park area.

As explained in the organization model, the organization hierarchy of FMM in a park area is represented by three entities: 'Administration', 'Organization' and 'Role'. In addition, there is a 'Person' entity inherits the duty of the 'Role' to perform specific maintenance related works.

Strictly speaking, there are four types of facility maintenance activities in a park area, namely, maintenance, inspection, renovation and repair. Here, the maintenance refers to an operational and functional servicing action to maintain a component in good condition, such as cleaning the surface of a machine or lubricating a moving part. Each type of an activity has a 'plan' entity and a 'task' entity except for the repair. A 'plan' sets the instruction details and cycle of the operation. Every other cycle there will be a new 'task' generated and assigned to certain 'person'. There is no 'plan' for repair activities because failures of components usually happen suddenly and hard to predict.

Maintenance and inspection are actions taken to prevent failures in the facilities. The specific manner or way by which a failure occurs in terms of failure of the component function under investigation is defined using the term failure mode [27]. A component can have multiple failure modes. When making a maintenance or inspection plan, the manager decides what actions to take according to what failure modes would likely happen on the facility components. For each failure mode, there are several check items for occurrence detection, in which, two entities 'Failure mode' and 'Check item' are used to represent the concepts. As for a repair work, there is usually failure reports from reporters requesting repair services. This is represented by 'Failure report' and 'Reporter'.

By referring to this model, databases reflecting the actual data concepts and relationships for the FMM in a park area can be built.

4.2. GIS-BIM integration mechanism

In the system, GIS and BIM are integrated to facilitate the retrieval and visualization of multi-scale data, where BIM is used to create, manage and share the FMM data of vertical facilities while GIS is used to store, manage and analyze data describing the horizontal facilities and the environment of a park area. As Fig 3 shows, the front-side of the system is composed of three parts, a GIS viewer, a BIM viewer and a business information viewer, each has bidirectional data connection to the relevant databases in the back-side. Records among the three databases are linked by GUID of the facility or component, making it possible for users to jump between GIS viewer and BIM viewer. In the GIS viewer users can browse 3D graphics of the entire park area at low Level of Detail (LoD) and query macroscale data. They can also select certain facility and jump into the BIM viewer to browse BIM models of the facility at medium LoD. If necessary, user can also focus on certain component to see detailed geometry at high LoD with the rest parts being hidden. The business information viewer is always visible and shows business related information such as task information according to the use case. For FMM in a park area, planning and management affairs can be finished in the GIS viewer and BIM viewer while tasks can be executed only using the BIM viewer. Jumping between different LoDs provides flexible 3D visualization and good display efficiency.

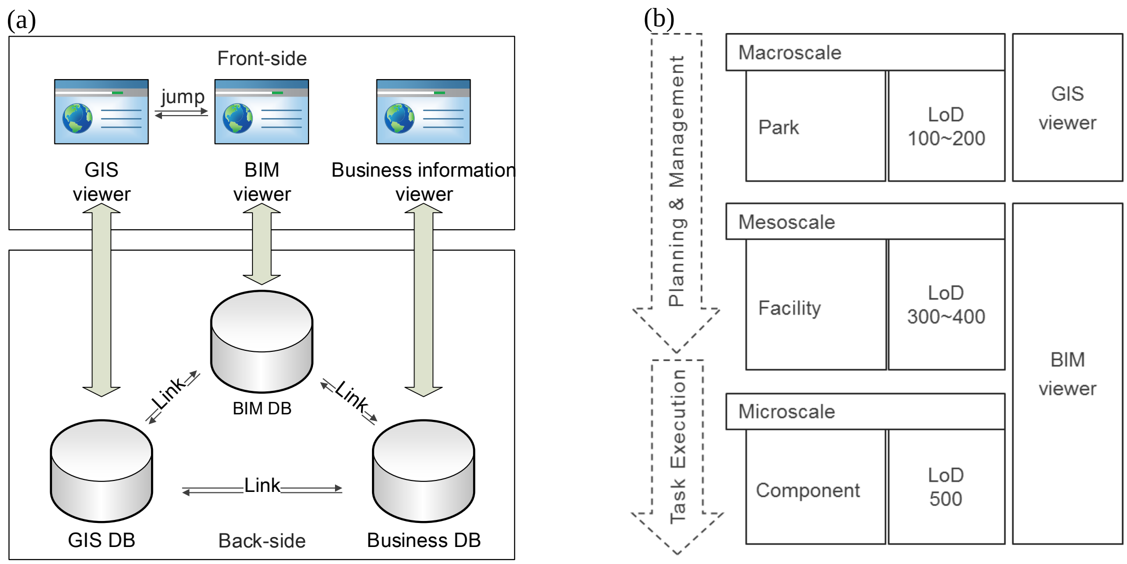

Fig. 3. GIS-BIM integration mechanism
(a) The technical architecture of GIS-BIM integration; (b) The schematic diagram of GIS-BIM integration for FMM in a park area.

4.3. Maintenance optimization mechanism based on RCM

RCM and Failure Mode and Effect Analysis (FMEA) are utilized for the facility maintenance optimization. RCM optimizes maintenance plan by prioritizing components of facilities and determining the appropriate type of maintenance strategies for them. There are mainly three types of maintenance strategies for facility maintenance, that is, the corrective maintenance (or reactive maintenance), the preventive maintenance and the predictive maintenance (or condition-based maintenance) [28]. Corrective maintenance is a simple strategy where a component in a facility will not get maintained until it breaks down. For this strategy, repair activity is mostly used. Corrective maintenance have the least life-cycle cost when failures seldom happen, but when emergency happens and causes a large amount of consequential damage to other components, the cost could be very expensive. Therefore, it is suitable for components with failures of low risk. Preventive maintenance is the strategy where maintenance tasks are performed in accordance with a predetermined plan at regular, fixed intervals to prevent failure occurrence at an early stage. For this strategy, maintenance activity is used. Preventive maintenance requires much labor and inventory for spare parts but can reduce the maintenance costs by avoiding the consequential damage. Therefore, it is suitable for components with failures of high risk and large occurrence probability. Predictive maintenance differs from preventive maintenance by basing maintenance need on the actual condition of the component rather than on some preset schedule. To initiate the preventive maintenance, the condition of a component must be monitored to identify whether there is any evidence of change from a normal condition to an abnormal condition. Inspection and sometimes sensors are used to monitor the condition. If a change representing an abnormal condition in the monitored parameter happens, a repair activity might be required. As we can see, predictive maintenance requires the most maintenance resources, so it is suitable for components with failures of extremely high risk.

FMEA is an engineering technique used to define, identify, and eliminate known and/or potential failures [29]. In FMEA, the Risk Priority Number (RPN) is calculated according to the effects, causes and detectability of each failure [30]. The calculation of the RPN is as follows.

$$RPN = S \times O \times D \quad (1)$$

In this formula, the parameter "*S*" refers to the severity of the failure mode, the parameter "*O*" refers to the possibility of occurrence of the failure mode and "*D*" refers to the detectability of the failure mode before it reaches the occupant. The value range of each parameter is from zero to ten.

For the maintenance optimization, FMEA is used to get all the failure modes of a facility component and calculate their RPNs. Prioritization of the components is performed based on the value of their largest RPN. Using the theory of RCM, assigning inspection plans to components with failure modes of large RPN, assigning maintenance plans to components with failure modes of medium RPN, and waiting for components with failure modes of low RPN to break then taking repair tasks will achieve the optimization of facility reliability and cost-effectiveness.

4.4. System architecture

The architecture of the proposed system is composed of four layers as shown in Fig 4. The top two are the Presentation Layer and the Business Layer. The Presentation Layer have a FMM Portal for the access from PC and a Mobile APP for the access from mobile phones or tablets. The Business Layer has nine modules to support different parts of the FMM in a park area. Inspection Management module, Maintenance Management module, Repair Management module, Renovation Management module and Failure Report Management module each supports the work flow of the corresponding maintenance activity. In Permission Management module, users create organizations and allocate information access permission to them. Similarly, in User Management module, users create roles and then allocate function access permission to them. In Performance Management module, users check the maintenance performance of each organization and crew worker. In Model Management module, users upload, update or delete BIM/GIS models for facilities or the park area.

The bottom two are the Service Layer and the Data Layer. The Service Layer provides shared functional services such as connection to the databases, GIS/BIM data presentation and user's location calculation for the Business Layer. The Data Layer, which is actually composed of databases, models, business attachments and system configuration files, is a very important managerial asset to the FMM in a park area.

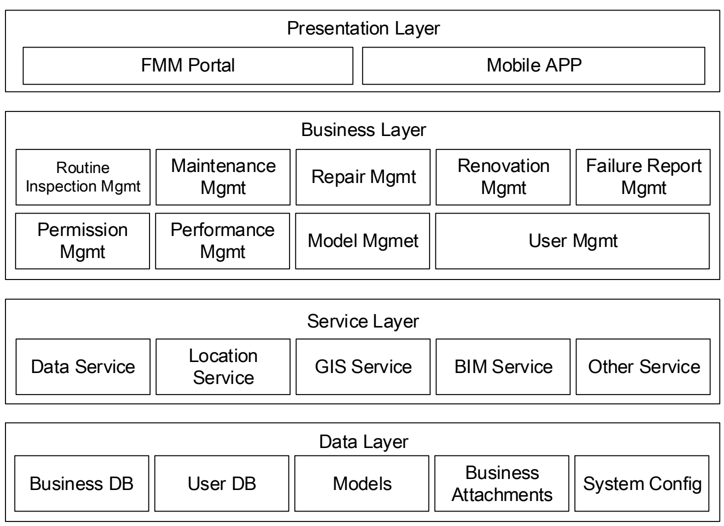

Fig. 4. Architecture of the proposed system.

5. Conclusions

The purpose of this study is to propose a system framework for FMM in a park area that solves two managerial problems, i.e. "poor information sharing between participating organizations" and "maintenance reliability and cost-effectiveness of the entire park area is unwarrantable". Through requirement analysis, this paper established a solution consisting of an information model for FMM in a park area, a GIS-BIM integration mechanism, a maintenance optimization mechanism based on RCM to formulate the system framework. The system framework is valuable for developing software systems that can support multiple FMM organizations of an area to work on the same platform, avoid managerial problems and achieve better performance.

A software system based on the proposed framework is now under construction. Future works of this study includes (1) designing the algorithm for the calculation of RPN, (2) integrating sensor data to support real-time condition monitoring.

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