CSCE Annual Conference
Growing with youth – Croître avec les jeunes

Laval (Greater Montreal)
June 12 - 15, 2019

DEVELOPMENT OF A BUILDING CONDITION ASSESSMENT FRAMEWORK BY LEVERAGING SUBSYSTEM RELIABILITY

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Abstract: In the hierarchical building management system, the building can be divided into three levels: system level, subsystem level, and component level. Furthermore, the building systems can be considered into eight categories, including: interior, shell, electrical, plumbing, conveyance, heating, ventilation and air conditioning (HVAC), fire protection, and equipment. Each system can be then framed into several subsystems consisting of multiple components at the component level. The appropriate condition assessments of a buildings need to systematically reflect the conditions of the subsystem or component level to reflect the complexity of the building system. The objective of this paper is to provide a Deferred Maintenance (DeM) mitigation strategy for the building condition assessment at the component, subsystem, and system levels. The proposed mitigation strategy framework for the DeM consists of five phases: (1) building selection, (2) system evaluation, (3) DeM component evaluation, (4) DeM subsystem model evaluation, and (5) total subsystem evaluation. Probabilistic risk analysis is applied in this research using reliability theory to consider the organic relationship with the building system leveraging fault tree analysis and Bayesian network analysis. Our proposed framework for the building condition assessment will allow the stakeholders and decision makers to prioritize strategies to address deferred maintenance backlogs at different levels of buildings. Furthermore, the result of the proposed DeM mitigation strategy framework will help in budget allocation to improve the long-term budgetary goal of physical asset management.

1 INTRODUCTION

Over the past several decades majority of public universities in the U.S. have confronted the challenge of facility management including Maintenance, Repair, and Rehabilitation (MR&R) strategies. In a survey of 400 institutions, Kaiser (Kaiser and Davis, 1996) examined the deteriorating state of higher education facilities in the U.S. The results of the survey concluded that $26 billion are needed to fix the accumulated deferred maintenance backlog with $5.7 billion for urgent maintenance needs. Historically, Bound and Turner (John Bound and Sarah Turner, 2002) mentioned that the sudden surge of student enrollment due to the G.I. Bill in 1945 led to an increase in the number of buildings in colleges and universities. More than half of the current campus facilities were built after World War II, when enrollment grew 600 percent, from 2.3 million students in 1950 to more than 20 million students projected by 2016 (Kaiser, 2015). During that same period, the number of academic institutions grew from 1,800 to more than 4,000 and facilities expanded dramatically. Now, sixty years later, the facilities that were built in the post-war period have been deteriorated considerably. Kaiser (Kaiser, 2009) pointed out the reason for the Deferred Maintenance (DeM): poor design and cost-cutting decisions caused inferior construction techniques, which lead to accelerated facility deterioration. As a result, DeM backlog has become a critical issue leading to failures of current facility management to fulfill their mission. Several phone interviews were conducted to explore the current issues related to DeM and to identify the problem statement at various universities. Based on the findings from the phone interviews, a DeM mitigation strategy framework is developed in this research to evaluate the building condition for DeM backlogs and prioritize the system, subsystem and components of the buildings. As a result, a new paradigm is proposed for the building assessment consisting of five phases: (Phase 1) building selection, (Phase 2) system evaluation, (Phase 3) DeM component evaluation, (Phase 4) DeM subsystem model evaluation, and (Phase 5) total subsystem evaluation. “Reliability” in this research is considered as the key performance index, and defined as the probability of the continuation of the performance of the system as designed (Andrews and Moss, 1993; Henley and Kumamoto, 1981; Huajian and Yongchang, 1995; McCormick, 1981; Pullum and Dugan, 1996). Specifically, the focus of this research is on developing subsystem reliability since the system level prioritization is too coarse and the component level prioritization is too granular to perform for the campus sized buildings. Additionally, during the acquisition of the subsystem reliability, the system and component level is systematically evaluated so that the facility manager may take advantage of the framework based on the system, subsystem, and component level. The proposed DeM mitigation strategy framework for the building condition assessment allows the stakeholders and decision makers to prioritize buildings at different levels to deal with deferred maintenance backlogs and improve the long-term budgetary goal of the physical asset management.

1.1 Phone Interviews

Several phone interviews were conducted to explore the current DeM issues at various universities to identify the problem statement. Six universities were interviewed for this purpose. The respondents were divided into two groups: public and private universities. The semi-structured interview protocol included questions about A) deferred maintenance issues, B) budget prioritization, C) funding sources, and D) improvement for DeM. Table 1 provides description of the universities that participated in the phone interviews.

Table 1: Participating Universities in the Phone Interviews

University	Private/Public	Enrollment	Location
1	Private	21,679 (14,282 undergraduate)	New York
2	Private	12,179 (8,448 undergraduate)	Indiana
3	Public	23,109 (14,682 undergraduate)	Georgia
4	Public	43,625 (28,395 undergraduate)	Michigan
5	Public	27,578 (18,347 undergraduate)	Michigan
6	Public	29,995 (19,882 undergraduate)	New York

When asked whether they consider DeM costs in their budget model, five universities suggested that they consider DeM in their budget models. One university, located in New York, did not consider DeM in its budget model and indicated that a large portion of their DeM backlog is addressed by capital renewal and renovation projects. Figure 1 shows that, in terms of the budget categories in which DeM costs are applied, most of the universities (71% of respondents) allocate DeM costs in their annual costs. Three universities have allocated DeM costs to an annual cost category as well as a one-time cost category. DeM costs would be assigned to the one-time cost category only when funds are available to do so. Some of the universities have used two methods for DeM allocation.

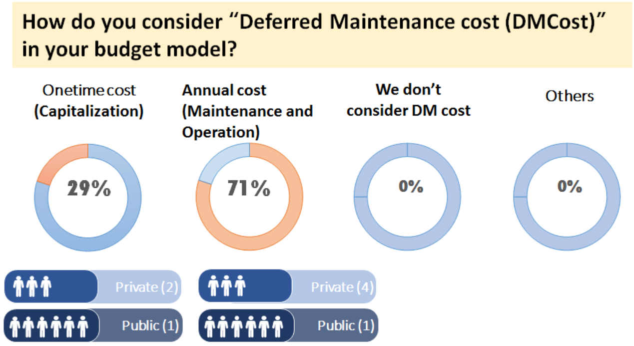

Figure 1: DeM Allocation

The universities were asked about the main cause factors for DeM (see Figure 2). Budget limitations (54.5%), increasing rate of deterioration (18.2%), and inappropriate MR&R strategies were the main reasons identified by the responses for most of the outstanding causes of DeM.

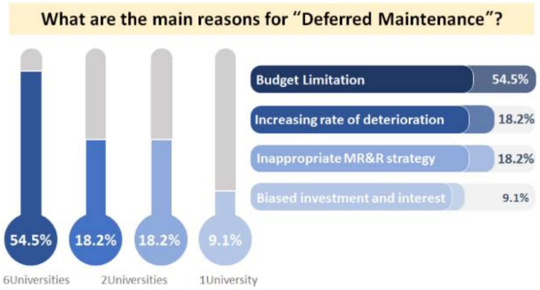

Figure 2: Causes of Deferred Maintenance

The next question asked about the prioritization of DeM funds. Most of the universities (83%) indicated that they did not prioritize between facilities for DeM, as they did not have any systematic evaluations to deal with DeM backlogs. Additionally, in the following question, the universities were asked about the criteria they consider when prioritizing funds for facilities. They consider safety issues to be the most important, followed by several other factors, such as mechanical failure(s), energy costs, and water influx issues like a leak in the roof.

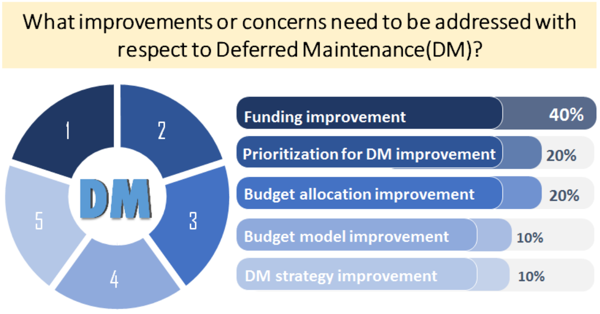

Figure 3: Research Needs

The last question of the interview inquired about improvements and considerations for DeM, research needs. Figure 3 indicates that funding improvements were the most important consideration (40%). Additional priorities for DeM improvements were budget allocation improvement (20%) and budget model improvement (10%). Participants provided several comments about current DeM problems that they face. In terms of the budget model, one university indicated that their budget model is based on only one fiscal year, which makes it challenging to implement a long-term MR&R strategy. One university reported that 85 buildings are 58-years-old and 20 buildings out of 85 require significant renovation such that the university faces a large DeM backlog. Another university estimated $250M for their DeM costs but reported that they cannot obtain that amount of funding. For example, donors prefer to put their names on new buildings rather than contributing to the renovation of old buildings. Hence, budgets for DeM tend to be limited and unattractive to the alternative sources.

To conclude, a small sample of interviews suggest that the main causes of DeM may be budget limitations (54%), an increasing rate of deterioration (18.2%), and inappropriate MR&R strategies. Additionally, inflation and increased government regulations have resulted in the reallocation of resources, which has driven these institutions to delay their major maintenance projects. To solve these DeM backlog problems based on the observations from the interviews, funding improvements, prioritization of DeM, budget allocation improvements, and budget model improvements are required. Therefore, the aim of this research is to develop DeM mitigation strategy framework to deal with prioritization issue and budget allocation for DeM backlogs.

2 METHDOLOGY

In this research an innovative framework is proposed to: evaluate the building condition, prioritize the deferred components, system, and subsystem. The framework consists of five processes: (P) building selection, (Phase 2) system evaluation, (Phase 3) DeM component evaluation, (Phase 4) DeM subsystem evaluation, and (Phase 5) total subsystem evaluation. Figure 4 shows the DeM mitigation strategy framework based on the hierarchical building management. The whole system classification is followed by Uniformat (Charette and Marshall, 1999; Decision and Report, 1990).

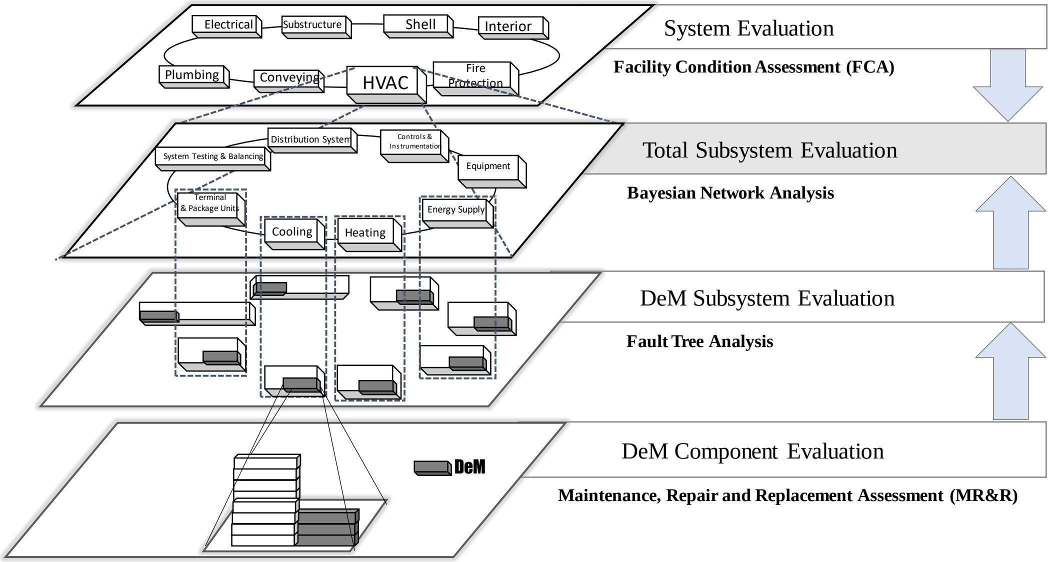

Figure 4: DeM Mitigation Strategy Framework

2.1 Phase 1: Building Selection

The Facility Condition Index (FCI) is an index for facility management benchmarks used to commonly assess current conditions of building assets. FCI is defined as the ratio of the DeM cost to the current replacement value (CRV). Building conditions are defined in terms of FCI values as follows: 0% to 5% (good), 5% to 10% (normal), 10% to 30% (poor), and exceeds 30% (critical or demolish)(Cerl and Note, 2006; Grussing and Marrano, 2010; Lewis and Payant, 2000). The FCI value is used in building selection by setting the target FCI value. If the target value of the FCI is 0.2, buildings that have a higher FCIs than 0.2 are selected. After the target building(s) have been selected the total DeM cost can be estimated by back-calculating using Equation 1.

[1] *FCI (Facility Condition Index) = Total estimated cost of the Deferred maintenance*

/ Estimated current replacement

2.2 Phase 2: System Evaluation

This research applied a key performance index called “Reliability” to assess the different levels of conditions (system, subsystem, and component level) of the buildings. Reliability is theoretically defined as the probability of success. It represents operability, i.e., the ability of a component or system to function at a specified moment or time interval (Endrenyi and Anders, 2006; Henley and Kumamoto, 1981; McCormick, 1981; Xie and Lai, 1996). Therefore, reliability reflects the probability that components will not fail within the subsystem for a given period of operation. The reliability of each subsystem and the reliability of systems consisting of these subsystems determine the stability or the condition of the building.

The first building evaluation is performed at the system level. Facility Condition Assessment (FCA) is a visual survey-based assessment of the facilities (Amekudzi and McNeil, 2008; Charette and Marshall, 1999). In the phone interviews all six universities responded that they conduct FCA every five year to assess the condition of the buildings. This research applied FCA proposed by NASA(NASA, 2008(a), NASA 2008 (b)) with five tiers from Excellent (1) to Bad (5). The five tiers can be transformed using best non-fuzzy performance (BNP) values (Hsieh et al., 2004; Opricovic and Tzeng, 2003). A fuzzy number generally aims to deal with imprecise numerical quantities in a practical way. In the BNP approach, the approximate fuzzy number (R_i) is calculated based on three values: LR_i, MR_i, and

UR_i, which are the lower, middle, and upper hypothetic performance values of the alternative i, respectively. The approximate fuzzy number (R_i) is explained by the equation 2 below:

[2] R_i = (LR_i, MR_i, UR_i)

where $R_i = \sum_{j=1}^{n} Lw_j \ X \ LE_{ij}$, $MR_i = \sum_{j=1}^{n} Mw_j \ X \ ME_{ij}$, $UR_i = \sum_{j=1}^{n} Uw_j \ X \ UE_{ij}$

Then, the triangular fuzzy numbers can be converted using the defuzzification value (Hsieh et al., 2004; Opricovic and Tzeng, 2003). The BNP value, called P(R_{sys}) can be calculated based on the 'center of area' shown in Equation 3. The BNP, P(R_{sys}), is considered as an indicator of system reliability in the study.

[3] $\mathrm{P}(R_{sys})$ = [(R_i - LR_i) + (MR_i - LR_i)]/3 + LR_i

For example, when HVAC is evaluted in the FCA, "excellent" out of the FCA (Tier 5) is estimated as 0.87 in the BNP, which represents 87% of reliability for HVAC.

2.3 Phase 3: Deferred Maintenance Component Evaluation

The assessment of reliability for the DeM components is in accordance with a life-cycle cost analysis (LCCA) based on Maintain, Repair & Replacement activities for the component (Whitestone Research, 2015). The useful life of the component can be defined as the operability of the system considering the component reliability throughout the life cycle. Several assumptions must be made for the LCCA: (1) the deterioration curve reflects linear deterioration rate (Yoon, 2012), (2) reliability is improved by 90 percent of the previous period of reliability (Yoon, 2012) and (3) reliability belongs to the family of lognormal distributions (Reliasoft, 2015). When the required activity is defined for the DeM component, the DeM costs can be given by the institution or can be created using the Whitestone Building Maintenance and Repair Cost Reference (Whitestone Research, 2014).

2.4 Phase 4: DeM Subsystem Reliability Evaluation

The reliability assessment of the higher system is performed in two levels: (1) DeM subsystem and (2) total subsystem. The total subsystem indicates the final outcome for the mitigation strategy framework for the DeM. In order to analyze the total subsystem, the DeM subsystem evaluation, a partial state of the total subsystem, should be preceded. The DeM subsystem reliability evaluation is analyzed with reliability consisting of DeM components. Each reliability of the DeM subsystem is derived by a series of reliability analyses of the lower-level DeM components shown in Figure 4. The series of reliability of the DeM components can be defined by Fault Tree Analysis (FTA). FTA is a powerful diagnosis technique and is used widely for demonstrating the root causes of undesired event in system failure, and logical functional relationship among components and subsystems of a system (Mendiratta, 2004; Pullum and Dugan, 1996; Stamatelatos, 2002). The relationships of the components can be standard logic symbols (AND, OR, Complex model).

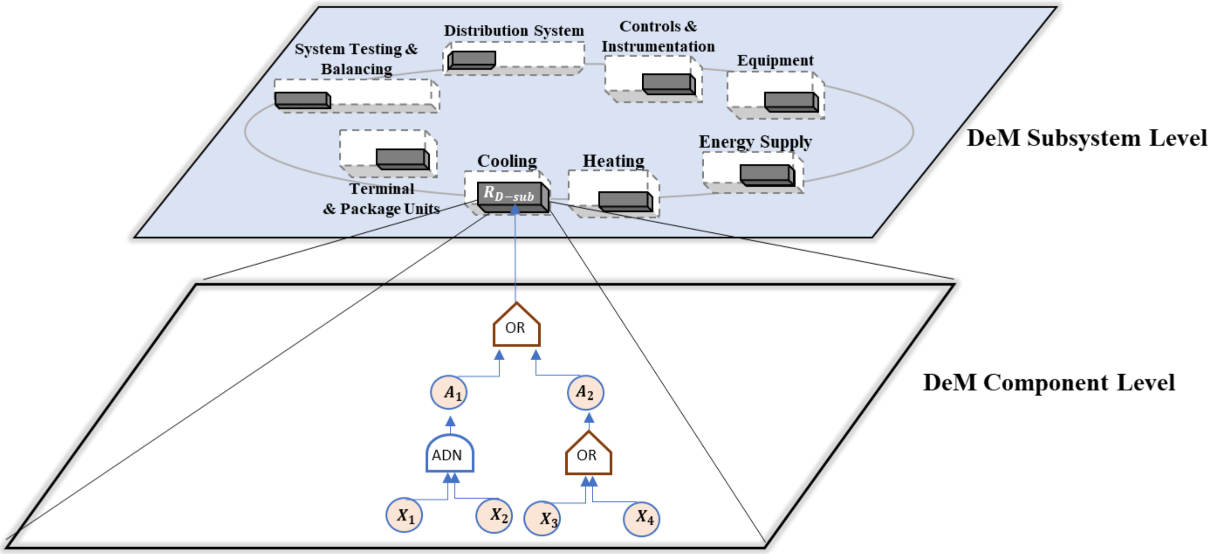

Figure 5: Example of Fault Tree Analysis

In the diagram shown in Figure 5, if there are four components X_1 to X_4. The two components X_1 and X_2 enter an AND gate, the union operation of events. Equation (4) describes the AND operation as follows:

[4] $R_1\ (X_1 \cup X_2) = P(X_1) + P(X_2) - P(X_1 \cap X_2)$

The other two components between X_3 and X_4 enter an OR gate, the intersection operation of events. Equation 5 describes the OR operation as follows:

[5] $R_2\ (X_3 \cap X_4) = P(X_3) \cdot P(X_4)$

As a result of the configuration of the four components, the DeM subsystem reliability (R_{D-sub}) of the top event can be stated as described in Equation 6:

[6] $R_{D-sub} = R_1 \cap R_2$

$R_{D-sub} = (X_1 \cup X_2) \cap (X_3 \cap X_4)$

The top event probability, which means the DeM subsystem reliability (R_{D-sub}) is calculated based on the series of the reliability of the DeM components.

2.5 Phase 5: Total Subsystem Reliability Evaluation

The total subsystem reliability is the integration between the DeM subsystem reliability and system reliability. In the hierarchical system diagram shown in Figure 5, HVAC reliability at the system level was evaluated through FCA (Phase 2), the individual DeM components including X_1 to X_4 were evaluated using LCCA (Phase 3) at the component level, The partial reliability of cooling at the subsystem level was evaluated by fault tree analysis based on the structure of the DeM components, X_1 to X_4 (Phase 4). The total reliability for cooling at the subsystem level is assessed by the conditional independent relationship between the reliability of HVAC from the system level and partial reliability of cooling from the DeM subsystem leveraging a Bayesian network (BN). BN is a probabilistic graphical model to explore uncertain domains by presenting the variables' relationships and corresponding conditional dependencies(Han and Delaurentis, 2013; Kang and Golay, 1999; Nadkarni and Shenoy, 2001; Nielsen and Jensen, 2009; Nishijima et al., 2007; Xing, 2010). As the DeM subsystem reliability (R_{D-sub}) is derived from a fault tree analysis, which affects the system reliability (R_{sys}), the system (R_{sys}) reliability could affect the total subsystem reliability (R_{sub}). Therefore, the total subsystem reliability can be defined by Equation 7:

$$[7]\ \mathrm{P}(R_{sub}) = \sum_{R_{D-sub},R_{sys}} P(R_{D-sub}, R_{sys}, R_{sub})$$

$$= \sum_{R_{D-sub},R_{sys}} P(R_{D-sub})\, P\big(R_{sys}\,|R_{D-sub}\big)P(R_{sub}\,|R_{sys})$$

The relationship between DeM subsystem and total subsystem is conditional independence. Following the entire process from Phase 1 to 5, the new metric, reliability, would be leveraged to prioritize the buildings as a composite index between macro and micro reliabilities. In this research probabilistic risk analysis is applied by using reliability theory to consider the organic relationship with the building system through fault tree analysis and Bayesian network analysis. Since the system evaluation is excessively macro and the component evaluation is excessively micro to prioritize for the campus sized buildings, the total subsystem reliability assessment would help facility managers or decision makers prioritize the DeM backlogs and set the budget allocation for the DeM backlogs. In addition, in the process of obtaining the reliability of the total subsystem, the system and component reliabilities are analyzed, facility managers or decision makers can monitor the building condition at different levels of the building system.

3 CONCLUSION

Deferred Maintenance (DeM) backlogs can increase the deterioration of the facility which may lead to the premature demolition of the buildings. Interviews with six major universities were conducted with the main purpose to explore and gauge the current issue of DeM backlogs at the universities. From the results of the interview question for the improvements with respect to DeM, it was revealed that funding (40%), prioritization for DeM (20%), budget allocation (20%), budget model (10%), and DeM strategy (10%) are critical improvments which need to be addressed. Accordingly, this research proposed DeM mitigation strategy to deal with prioritization for DeM and budget allocation for DEM. The proposed framework for the DeM consists of five phases: (Phase 1) building selection, (Phase 2) system evaluation, (Phase 3) DeM component evaluation, (Phase 4) DeM subsystem model evaluation, and (Phase 5) total subsystem evaluation. The key performance unit was set as “reliability” and used to evaluate the condition of each level of the building system. Facility Condition Index(FIC) for the building selection (Phase 1), Facility Condition Assessment (FCA) with non-fuzzy performance (BNP) for the system evaluation (Phase 2), life-cycle analysis approach for the component evaluation (Phase 3), Fault Tree Analysis for the partial subsystem evaluation (Phase 4), and Bayesian network analysis for the total subsystem evaluation (Phase 5) are applied to obtain the reliability at each level and to develop the building condition assessment. The benefit of the proposed DeM mitigation strategy for the building management is that once each level of evaluation is completed, the subsystems for the selected buildings can be prioritized by subsystem reliability, which is a composite index between macro level as the system reliability and micro level as the component reliability. The subsystem reliability would allow facility managers to evaluate the healthy condition of the building from the component to the system level, also to provide the appropriate decision making to allocate the budget for the DeM component’s backlogs considering system and subsystem conditions at the same time. Therefore, the proposed mitigation strategy framework for the DeM will provide the new paradigm for the building assessment (1) to diagnose the current facility condition, (2) to prioritize the system, subsystem, and component holistically or individually, and (3) to decide the appropriate DeM budget allocation strategy.

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