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# CRITICALITY ASSESSMENT OF HOSPITAL BUILDING SYSTEMS

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**Abstract:** Healthcare facilities are one of the most important assets in a country as their number and quality are common measures of the society's prosperity and quality of life. Hospitals are considered the most complex type of healthcare facilities to operate and maintain as they should work 24/7 with maximum performance and any mistake could cost the lives of many humans at a time. Although Canada is one of the highest countries all over the globe in the health spending, the status of the Canadian hospitals was described in numerous reports and statistics as a crumbling status as their overall condition received a "POOR" grade based on their deferred maintenance and current replacement values. This was associated with the maintenance strategies implemented inside the hospital buildings. As a result, this paper recognizes the need to implement a more efficient maintenance strategy instead of the currently implemented approaches to increase the performance of hospital buildings and efficiently make use of the funds assigned for healthcare facilities. As a preliminary step, this paper assesses the criticality of the various hospital systems and accordingly creates a maintenance strategy selection tool for the different hospital systems. Experts were interviewed regarding this matter and their opinions were analyzed using multi-criteria decision-making tools and techniques to evaluate the weight and importance of all hospital systems using pair-wise comparison methods, representing the relative effect of the various systems on the total hospital performance. The proposed framework can be used by facility and maintenance managers to facilitate the decision-making process regarding maintenance, repair, replacement and renovation activities of hospital buildings and healthcare facilities.

## 1 INTRODUCTION

Aging and deferred maintenance have been identified as the most significant problems faced by hospital building assets across North America (ASHE 2017). According to HealthCareCan (2015), the average condition of hospital buildings across Canadian provinces is a poor condition, and the Canadian Infrastructure Report Card (2016) revealed that this condition is most likely to continuously deteriorate in the future. Following a reinforcing loop relationship, the deterioration of hospital components leads to increasing the maintenance requirements which by turn increases the budget required for maintenance works. However, due to the limited funds allocated to upgrade the status of hospital buildings as well as the inappropriate maintenance strategies implemented inside the facilities, this often leads to deferring a significant amount of the maintenance work which contributes to the further deterioration of the building assets. Delaying maintenance and using inefficient maintenance strategies have also proved to be key players in decreasing the overall performance of the building as well as increasing the adverse impact of the building assets on the environment (Thomas et al. 2015). Therefore, this study proposes a novel maintenance strategy selection method especially developed for hospitals and healthcare facilities taking into consideration the variable criticality among the building systems. This research would be of great assistance to facility and asset managers as well as decision makers in the effective planning, scheduling and prioritization of hospital components for inspection, maintenance and capital allocation purposes.

## 2 BACKGROUND

A significant amount of researches have assessed the criticality of the infrastructure assets, facilities and their dependent components as a means to facilitate the prioritization and optimization of maintenance interventions scheduling and planning. Other researches have tackled the maintenance strategy selection process and studied the different ways of determining the optimum maintenance course of action to be applied for the asset components (Yousefli et al. 2017). Despite the vast amount of studies related to the aforementioned subjects, the integration between the criticality assessment of components in order to select the most suitable maintenance strategy to be applied for each component is considered a gap identified from the literature search, that this paper is aiming to fill.

Criticality of infrastructure components has been studied by several researchers as part of the risk assessment process in order to assess and evaluate the importance and significance of the different asset components and their effect on their surroundings. Theoharidou et al. (2010) described the criticality assessment process, as a process in which the criticality level of the asset components is evaluated and appraised. As mentioned by Youance et al. (2016), it is of high importance to assess the failure consequences and scenarios of the asset and the interdependencies between its components in order to determine the overall criticality and reliability of a system.

Miles et al. (2007) defined the term “Criticality” as the degree of seriousness of the failure occurrence in a facility, while Salman et al. (2011) defined criticality as the consequence of failure of the assets and their components. Critical assets were defined by Syachrani et al. (2013) as the assets having high probability of failure and a high expected impact if the failure occurs. In this research, criticality factors are identified in order to prioritize and select the most appropriate maintenance intervention to be applied to each group of components in the hospital building.

Reviewing the literature, a variety of criticality factors are acknowledged and analyzed for applicability in hospital environments as summarized in Table 1.

Table 1 Summary of Main Criticality-Related Literature

| Reference | Year | Type of Asset | Criticality Factors |
|---|---|---|---|
| Salem and ElWakil | 2018 | Medical Equipment | Physical Assessment, General Safety, Infection Prevention, Revenue Lost |
| Melani et al. | 2018 | Power Plant | Environmental Impact, Energy Generation Impact, Patrimonial Impact |
| Kaddoura and Zayed | 2018 | Pipelines | Environmental, Economic, Public |
| Hammad et al. | 2014 | Building Assets | Physical Condition, Effect on Occupants, Effect on Assets, Maintenance Cost |
| AbouHamad and Zayed | 2013 | Subway Stations | Size, Nature of Use, Location |
| Taghipour et al. | 2010 | Medical Equipment | Function, Mission Criticality, Age, Risk, Recalls and Hazard Alerts |
| Miles et al. | 2007 | Pipelines | Environmental Impact, Size, Transportation Impact, Ease or Repair and Reliability |
| Hahn et al. | 2002 | Pipelines | Human Health, Environmental, Commerce, Traffic, Reconstruction |

The primary objective of assessing the criticality in the literature was to serve as a tool for efficient scheduling of maintenance work orders, without considering which type of maintenance should be used for each asset. This study focuses on analyzing the hospital building components and the various approaches to maintenance and accordingly select the most suitable maintenance strategy for each hospital component. The main goal of the various maintenance strategies is to upgrade the overall condition of the facility or asset while maintaining a reliable overall performance. To achieve this goal, different paths can be taken by facility managers and maintenance personnel to plan and execute the maintenance and repair activities. The currently applied maintenance strategy in hospital buildings in North America is mostly Reactive/Corrective Maintenance. However, there are other approaches that are deemed more suitable for application in a complex environment like hospital buildings. Below is a definition for each of the maintenance intervention course of actions available in the literature and in practice that can be applied to facilities of a dynamic nature like healthcare facilities.

*Reactive Maintenance:* The reactive maintenance approach is also known as being a “Run-to-Failure” method as building components are only repaired/replaced when failure occurs. Although this method keeps scheduling and inspection costs and staff to a minimum, it is a very costly approach when failure does happen as an unplanned event. (Schneider et al. 2006 and Ruparathna et al. 2017).

*Preventive Maintenance*: The preventive approach is one in which work is scheduled in a time-based manner, where time-intervals are identified based on past experience or manufacturer manuals (Wang et al. 2014). It is mainly intended to perform the proper maintenance action to the components before the actual wear or failure. (Ruparathna et al. 2017).

*Predictive Maintenance*: The predictive maintenance plan depends on evaluating the current condition of the components, expecting its future condition and deterioration pattern and accordingly the maintenance interventions are scheduled. This is considered a more cost-effective strategy than preventive and reactive maintenance as it eliminates and controls casual stressors prior to any significant deterioration in the component’s condition (US Department of Energy 2010).

*Reliability-Centered Maintenance*: This maintenance procedure combines all the previously mentioned approaches by being concerned with both, the condition of the components as well as the overall performance and reliability of the system/building. The maintenance interventions are evaluated and ranked which eliminates unnecessary actions and also reduces the probability of component failure by ensuring that the most suitable maintenance action is taken with respect to each separate component inside the building facility (NASA 2008).

For the purpose of this study, the Reliability-Centered Maintenance is adopted to develop the Criticality-Based Maintenance Management Framework used. The framework developed as part of this study determines the failure impact of the different hospital components and assesses their importance inside the hospital facility with respect to their purpose, location and service life; and accordingly identifies the ideal maintenance intervention to be applied for each system inside the hospital buildings and healthcare facilities.

## 3 METHODOLOGY

The proposed methodology in this study comprises of two main phases: Data Collection phase and Framework Development phase. In the first phase, the current practice and available literature related to planning, scheduling, classification and selection of the maintenance and repair activities implemented inside buildings and healthcare facilities are reviewed and studied to identify the gaps and limitations of all the methods used and developed in previous researches. Accordingly, the objectives of this study have been realized to fill those gaps and overcome the limitations of the preceding approaches. The failure consequences and impacts of the various hospital components were identified and categorized into two major categories having ten criteria representing the critical significance of the components. After that, a survey questionnaire was developed and unstructured interviews were conducted to gather the opinions of experts in the field of hospital and building assets facility management regarding the asset hierarchy proposed, the criticality assessment factors identified, as well as the relative weighting and rating of the different factors with regards to the varying hospital components.

Consequently, an Importance Index (II) is calculated for each hospital building system based on four criteria of evaluation. After that, the Component Failure Importance (CFI) of each component is valued based on six identified criteria comprising five sub-factors. The calculation of the weights of each of the considered factors and subfactors in the criticality assessment process follow a Fuzzy-Analytic Hierarchy Process (F-AHP) to reduce any possible subjectivity of the experts' opinions or any uncertainties resulting from the surveying process. Following the development of the F-AHP model, each hospital building system is given a criticality score on the basis of a Multi-Attribute Utility Theory (MAUT) that results in a weighted equation representing the criticality evaluation process to be applied for any hospital component.

Furthermore, the Importance Index (II) and the Component Failure Importance (CFI) are used in this study to derive the Criticality Index (CI) that further helps in the selection of the most appropriate maintenance intervention to be applied for the different systems inside the hospital building as shown in Figure 1.

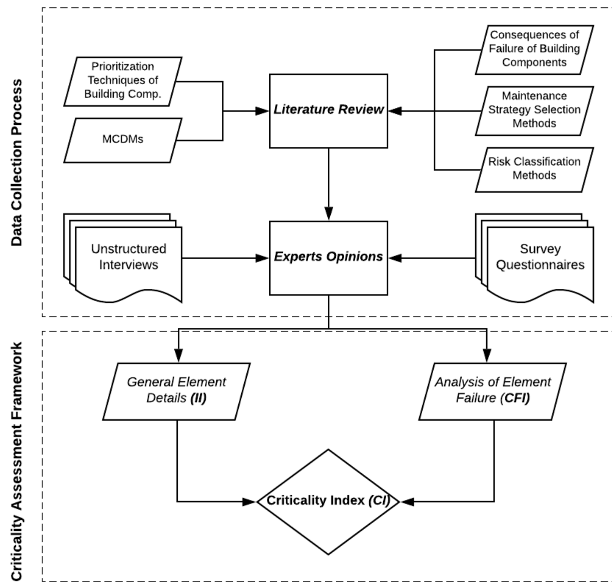


Figure 1 Overview of Research Methodology

## 3.1 Hospital Hierarchy Classification

The hierarchy of the hospital building components adopted in this research is a quadruple-level organization based on the OmniClass Construction Classification System as shown in Figure 2. The hospital building is divided into four zones namely: Acute Care and Emergency (ACE), Ancillary and Support Division (ASD), Diagnostics and OutPatient Clinics (DOC) and InPatient Wards (IPW). Each of the four zones is decomposed into six systems representing the main categories of components inside the hospital building. The systems are further decomposed into subsystems to facilitate the maintenance and inspection scheduling and implementation. Some systems have been modified from the OmniClass and tailored to healthcare facilities like the plumbing system components, due to the complexity of such a system in hospitals in relation to other building types.

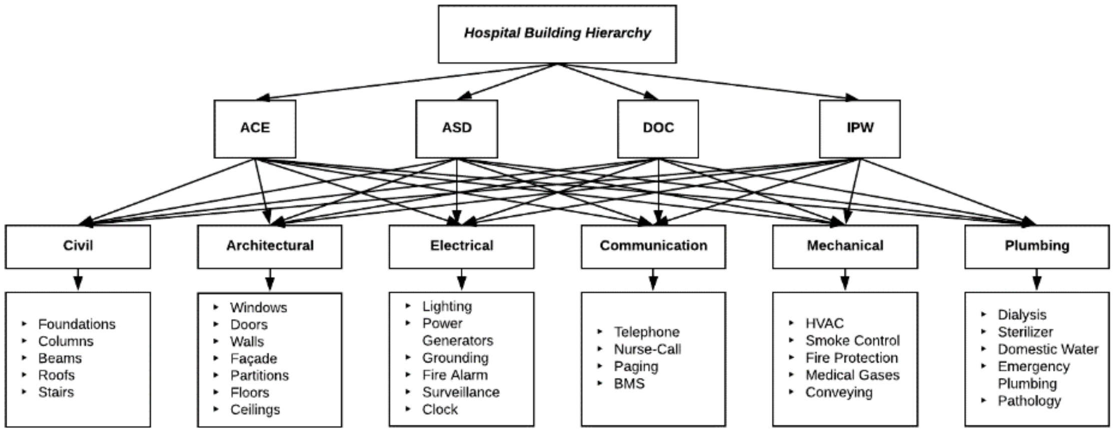


Figure 2 Hospital Building Hierarchy

### 3.2 Criticality Assessment of Hospital Systems

In this research, the criticality of the various systems present inside the hospital building is calculated using two parameters: The Importance Index (II) and the Component Failure Importance Indicator (CFI). The Importance Index obtains a weighting scheme for the building components based on their standing in relation to other components. While the Component Failure Importance evaluates hospital components against a number of factors representing the expected implications due to failure or breakdown of those components. Hence, the two values obtained are used to calculate the Criticality Index (CI) of each hospital system on a two-stage Multi-Criteria Decision Making (MCDM) technique, so that an appropriate maintenance strategy can be suggested accordingly.

#### 3.2.1 Importance Index Calculation

As previously mentioned, the importance index is an indicator that quantifies the significance of the various systems and subsystems by means of an evaluation against four criteria representing general details related to the components. The four criteria used to derive the Importance Index of hospital systems are: 1) the Purpose of the system usage, 2) the Location of the system inside the hospital facility, 3) the Redundancy available for the system, and 4) the relative Age of the system with respect to its useful life.

The weights for the four identified importance factors are obtained using a Fuzzy Analytic Hierarchy Process (F-AHP) using a scale from 1 – 9. The detailed description of the scale used is provided below in the Table 2 (Aydin and Kahraman 2011).

Table 2 Importance Index Pair-Wise Comparison Scale

| Rating Scale | | Linguistic Description |
|---|---|---|
| | (0,0,0) | Just Equal |
| 1 | (0,1,3) | Equally Important |
| 3 | (1,3,5) | Moderately More Important |
| 5 | (3,5,7) | Strongly More Important |
| 7 | (5,7,9) | Very Strongly More Important |
| 9 | (7,9,9) | Extremely More Important |

After the weights are calculated, the consistency ratio is then determined in order to verify the assigned weights. Weights are assigned to criteria only if the Consistency Ratio (CR) has a value less than 0.1.

### 3.2.2 Component Failure Importance Evaluation

Based on the literature search, verified by opinions of experts interviewed and surveyed, the main categories to evaluate the significance of the failure or breakdown of the components inside the hospital are collected. The factors gathered are categorized into six main categories. The first four categories representing the consequence of the system failure, are: Operational Impact which deals with factors affecting the overall service provided by the hospital building, Environmental Impact factors affecting the surrounding outdoor and indoor environments, Social Impact factors affecting the occupants, patients and visitors inside the building and Financial Impact factors dealing with financial aspects and resources consumption due to failure occurrence or corrective actions taken to restore the condition of the component. The remaining two categories are the failure occurrence rate, and the possibility of failure detection prior to occurrence. The criteria and sub-criteria chosen to evaluate the importance of failure of hospital components are given in Table 3.

Table 3 Component Failure Importance Criteria and Sub-Criteria

| | Criteria | Sub-Criteria |
|---|---|---|
| 1 | Operational Impact | **Op.1** Systems' Interdependence<br>**Op.2** Mission Dependability |
| 2 | Environmental Impact | **En.1** Indoor Environmental Quality<br>**En.2** Emissions, Toxic Releases and Contamination |
| 3 | Social Impact | **So.1** Health, Sanitation and Safety<br>**So.2** General Human Comfort |
| 4 | Financial Impact | **Fi.1** Cost of Repair/Replacement<br>**Fi.2** Resources Needed<br>**Fi.3** Downtime |
| 5 | Occurrence | |
| 6 | Detectability | |

As illustrated in the preceding table, the Operational Impact of the component failure is evaluated based on two criteria, 1) Systems' Interdependence which represents the availability of dependent systems whose operation might be altered as a result of the system's failure, 2) Mission Dependability which is the effect of the system's failure on the overall mission and service delivery of the hospital. The Environmental Impact is assessed based on the effect of failure on the Indoor Environmental Quality inside the hospital space or zone, as well as the possibility of emissions, toxic releases, or contaminations as a result of the systems failure. The third criterion is the Social Impact which is related to the occupants of the hospital building, and evaluates the effect of the failure on the health, sanitation and safety of hospital occupants, and the effect on the general human comfort of the hospital occupants as well. Moreover, the Financial Impact of the failure of a hospital system is to be quantified based on the expected cost of repair or replacement of component, the resources required to perform the repair activity in terms of labour hours, and the downtime anticipated as a result of the failure in order to restore the component's condition. The Occurrence criterion included in the evaluation process is a measure of the rate of component's failure based on experience of previous events. While the Detectability parameter assesses the possibility of detecting a failure in the component being studied before the actual occurrence of the failure.

Following the same procedure followed in the Importance Index calculation, the factors and sub-factors identified for the Component Failure Importance are weighted based on pair-wise comparisons. Each of the hospital systems and their dependent sub-systems is then evaluated against the previously stated factors and sub-factors following a Multi-Attribute Utility Theory (MAUT) approach.

The MAUT is implemented to derive the ranking of systems and subsystems according to the F-AHP-based weights of each criterion, as well as the scores given to all subsystems for each given criterion as shown in Equation 1.

[1] $CFI = \sum_{i=1}^{n} \mathrm{Wi}\ x\ \mathrm{Ui}$

CFI = Component Failure Importance for a given subsystem; n = number of evaluation criteria; Wi = importance weight of each criterion; and Ui = alternatives' utility score.

After the pairwise comparison matrices were formulated and the experts' opinions were collected, the consistency ratio was then checked to be less than 10% to guarantee the consistency of the results. Finally, the Component Failure Importance was calculated for each sub-system by multiplying the weight and utility score of each component through Equation 1.

### 3.2.3 Criticality Index Calculation

Upon completion of the previous two stages, a criticality index is obtained for each hospital system to help in the selection of the ideal maintenance strategy to be applied for that specific system, as part of the criticality-based maintenance strategy selection approach followed in this research. The criticality index for each building system is derived from the multiplication of its importance index by the component failure importance score as illustrated in Equation 3.

[3] $CI = II\ x\ CFI$

CI = Criticality Index of a hospital system; II = Importance Index of the system and CFIS = Component Failure Importance score of the system.

The criticality index of each component calculated in this section represents the level of the expected impact for the component's failure or stoppage and is an indicator for its importance and significance to the hospital operation and finances, the occupants and patients as well as the environment. A normalized criticality level indicative scheme is followed in this paper as shown in Table 4 to identify the most critical components of the hospital building and accordingly schedule the maintenance work based on the critical priority of components. The criticality level of hospital components can also be used further to select the most appropriate maintenance intervention to be applied for every building system.

Table 4 Normalized Criticality Scheme for Hospital Building Systems

| Ranking | Criticality / Impact |
|---|---|
| 0 – 0.30 | Low Criticality |
| 0.30 – 0.65 | Moderate Criticality |
| 0.65 – 1 | High Criticality |

To interpret the criticality level scheme developed, a criticality index between 0 – 0.30 would probably suggest that the component being studied is in a location inside the hospital having low importance or serves a non-critical purpose. Also, the failure of such a component would probably result in a minor disruption to the hospital mission and a minor financial loss as well, and the health and safety of the occupants and the surrounding environment would not be affected. To components of this level, a reactive maintenance approach can be assigned as the impacts and consequences of their failure are almost negligible. On the other hand, a criticality index of 0.65 – 1 would be complementing a component of a significant expected effect on the safety and health of occupants and on the surrounding environment, which would result in a high financial loss and interruption to the operability and function of the hospital facility. This would strictly mean that those critical components should be assigned a proactive maintenance approach to keep those failures to minimum by determining the root cause of each failure and correcting it before the actual failure occurrence. The adverse effects of those components' failure can be omitted with a predictive maintenance strategy that expects when the failure is expected to occur and accordingly perform precautionary maintenance actions. In between those two extreme values of the criticality index, a preventive maintenance approach can be applied to components of moderate criticality as they would probably cause a moderate breach of the hospital operation and the environment but their effect on the human health and safety can be considered as an intolerable effect even if it is only of a moderate level.

## 4 MODEL IMPLEMENTATION

The preliminary calculations for the weights and scores for the previously discussed methodology have been completed for one questionnaire to serve as an illustrative example for the proposed approach. The factors affecting the Importance Index of the hospital systems were evaluated using pair-wise comparisons resulting in the values shown in Table 5. Calculation results suggest that the most significant factor in the Importance Index calculation is the Purpose of system usage followed by the Location of the system inside the facility. After that, the service life of the component proved to be of higher importance than the redundancy available for hospital systems.

Table 5 Importance Index Factor Weights

| Criteria | Importance |
|---|---|
| Purpose | 0.37 |
| Location | 0.26 |
| Redundancy | 0.13 |
| Age | 0.24 |

The next step was to calculate the weights for the factors and subfactors affecting the CFI indicator evaluation as shown below in Table 6.

Table 6 Weights for CFI Criteria and Sub-Criteria

| Criteria | Weights | Sub-Criteria | Local Weights | Global Weights |
|---|---|---|---|---|
| Operational | 0.11 | Effect on Other Components | 63% | 0.0693 |
| | | Overall Mission | 37% | 0.0407 |
| Environmental | 0.14 | IEQ | 61% | 0.0854 |
| | | Emissions, Toxic Releases and Contamination | 39% | 0.0546 |
| Social | 0.20 | Health and Safety | 75% | 0.15 |
| | | Human Comfort | 25% | 0.05 |
| Financial | 0.24 | Cost of Repair | 43% | 0.1032 |
| | | Resources Needed | 31% | 0.0744 |
| | | Expected Downtime | 26% | 0.0624 |
| Occurrence | 0.18 | | | 0.18 |
| Detectability | 0.13 | | | 0.13 |

The global weights of all the previous criteria are then used as part of the MAUT methodology to assign a rating for each building system against each of the identified factors based on the fuzzy scores given to systems that represent the level of urgency of their repair in a hospital building environment. The fuzzy score scheme is given in Table 7 (Kahraman and Kaya 2012).

Table 7 Fuzzy-Scoring Scheme for Impact Factors and Sub-Factors

| Linguistic Scale | Fuzzy Score Points |
|---|---|
| Very Low | (0,15,30) |
| Low | (15,30,45) |
| Medium | (30,45,60) |
| High | (45,60,75) |
| Very High | (60,75,90) |

The final step is the calculation of the Criticality Index of all hospital systems by multiplying the Importance Index by the Component Failure Importance. Consequently, the scores for the Criticality Index normalized and ranked; and accordingly, the most suitable maintenance strategy is assigned for each hospital building system based on their criticality.

## 5 CONCLUSIONS

Deterioration of building assets is an inevitable process that has to be controlled and monitored so it can eventually be minimized. Controlling deterioration is done by applying suitable maintenance, repair and capital renewal interventions whenever an asset needs it. Hospital are considered one of the most complex building assets to manage and maintain, however, their performance is of crucial importance as there human lives at stake. This makes an efficient maintenance strategy mix a very important decision to make for such complex environments like healthcare facilities. Therefore, this paper proposes a maintenance strategy selection framework that assess the criticality level of assets inside a hospital building and accordingly assigns a maintenance intervention to it. This is done by first analyzing the importance of each hospital component based on several factors, and then, their consequences of failure are evaluated and consequently, each component is given an indicative score of its level of urgency. Selecting maintenance strategies for building assets based on their level of criticality is considered a novelty of this research. The framework developed as part of this study is based on Multi-Criteria Decision-Making (MCDM) methods integrated with Fuzzy Logic (F-AHP and F-MAUT). This paper presents a useful tool to facility managers and decision-makers to help in the process of maintenance planning and scheduling as well as efficient capital renewal funds allocation.

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