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Neutrosophic-AHP-based GA Model for Renewals Planning of Hospital Building Assets

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Abstract—**Healthcare building infrastructure in Canada is currently facing two problems: Aging and Deferred Maintenance, leading to an increase in unexpected failures causing interruptions in the hospital operation which in turn affects the health and safety of its occupants. Despite the efforts exerted to overcome this, solutions cannot be easily implemented as they are often faced with limited and insufficient funds. Therefore, previous researches have experimented ways targeting a reduction in the rehabilitation costs while sustaining an acceptable physical condition of hospital assets. However, there is more to a building's performance than its physical condition. Hence, this study assesses the hospital performance by including functional parameters of components rather than solely evaluating their physical condition on the basis of an integration between Neutrosophic Logic and Analytic Hierarchy Process, and accordingly improves the rehabilitation decisions by utilizing the output from the previous model as an objective for a genetic algorithm optimization model to prioritize rehabilitation activities within a limited funding allowance. The developed model was validated by applying it to a real hospital situation where the results obtained from the model were compared to the actual output attained from rehabilitation works inside the hospital facility, and the model developed in this study outperformed the current practice by an improvement of 34%. This framework is expected to aid decision-makers in efficiently allocating rehabilitation funds to the most critical hospital building systems which in turn improves the performance and availability of hospital assets.**

Keywords—Neutrosophic Logic, Analytic Hierarchy Process, Genetic Algorithm, Renewals Optimization, Healthcare Facilities

I. Introduction

The healthcare industry has experienced a tremendous growth over the years and is projected to grow even more. In Canada, the healthcare expenditure currently represents 11.6% of the GDP (Gross Domestic Product) and this value is expected to keep rising till it reaches 19.4% by the year 2027 [1]. This is associated with several reasons including the increased demand for healthcare due to population growth, immigration, as well as the increased demands of baby boomers [2]. This has led to a shift in the nature of hospital-related projects from the construction of new facilities to repairing, renovating and upgrading the current ones. As reported in the literature, the number of hospital rehabilitation projects in recent years is almost triple the amount of new hospital construction projects [3].

Rehabilitation activities carried out in the healthcare facilities are considered an enormous challenge compared to the maintenance actions implemented in any other type of institution. This is mainly due to the complexity of hospital buildings as well as the high correlation between the activities executed and the safety of patients and their well-being [4]. The patient-safety concern entitles that the decision taken to repair, renovate or retrofit a hospital building component should be efficient and wise as it is far more critical than that of most other service-providing organizations and facilities. [2] and [5].

II. Background

One of the preliminary steps taken to facilitate the decision-making process regarding maintenance and rehabilitation of hospital components is the assessment of the current condition observable within the facility. This is usually followed by predicting the possible deterioration in the inspected components and finally selecting the most suitable rehabilitation activity to restore the condition of the component to an operationally acceptable level. The inspection process of building components mainly aims at evaluating their current condition level and the extent of defects and distresses present [6]. For this purpose, previous researches have proved that visual inspection is the most suitable approach to assess the condition of the majority of hospital building components [7].

Visual inspection is an evaluation procedure undertaken by experienced engineers to estimate the physical condition of the components using one of two methods: Distress Surveying method which is an accurate and reproducible approach that identifies the reason for the component failure based on a categorized list of possible generic distress types [8], while the second method is Direct Condition Rating which is less accurate than the distress survey but is proven to be faster and more applicable for assessing the condition level of building components against a set of criteria and benchmarks for the purpose of choosing the most suitable rehabilitation action to be taken [9].

Despite the importance of assessing the physical condition, other important parameters are also inevitable in the evaluation process of the performance of building assets and components, especially healthcare facilities due to their significance and complexity previously discussed. Extensive researches have been conducted with the aim of enhancing the current performance assessment process of building components, some of which are presented in the paragraphs to follow.

Reference [10] established a framework to evaluate the physical condition of building components that considers space as the basic building element unlike other models following the UniFormat building hierarchy of systems and subsystems in their inspection process. This model primarily assessed all components in one space then integrated the space results with other areas of the building. Reference [7] built upon the previous framework and identified four key performance indicators to evaluate the performance of a hospital building component namely: Physical condition, level of service, risk of failure and sustainability level. The physical condition of systems and subsystems as well as their sustainability level and risk of failure are assessed by means of a direct condition rating on a four-point scale, while the level of service is related to the zone where the building system being inspected is located and is a measure of the indoor air quality parameters including noise level, lighting and temperature. On the other hand, [11] developed a condition assessment model that incorporates an analytic hierarchy process to measure the physical condition of the building components by means of a direct condition rating on a scale from 1 to 9, as well as their effect on the building occupants, the impact of their damage on the neighboring assets, and the maintenance cost associated with restoring the condition of the component. Moving forward in this direction, [12] assessed the priority of hospital building systems condition by integrating the analytic hierarchy process with multi-attribute utility theory to evaluate five aspects of the hospital components' criticality level, namely: Operational, environmental, social and financial impacts of failure as well as the failure trend of the inspected component group.

The previously mentioned models have proved a significant improvement in the performance assessment process of healthcare facilities and building assets, however they lack some important factors for evaluation like the code compliance of the building components that measures the adherence of the system to safety and building codes, as well as the capacity appropriateness of the system that evaluates the ability of a system to sustain design conditions as well as increasing demands. As a result, this paper will attempt to fill those gaps by developing a more comprehensive performance assessment framework for hospital buildings and healthcare facilities to be used in efficient decision-making regarding operation, repair, and rehabilitation of healthcare infrastructure. Neutrosophic Logic was involved in the Multi-Criteria Decision-Making model developed within this research to keep the uncertainties, ambiguities, and imprecision of human decisions and preferences to a minimum.

III. METHODOLOGY

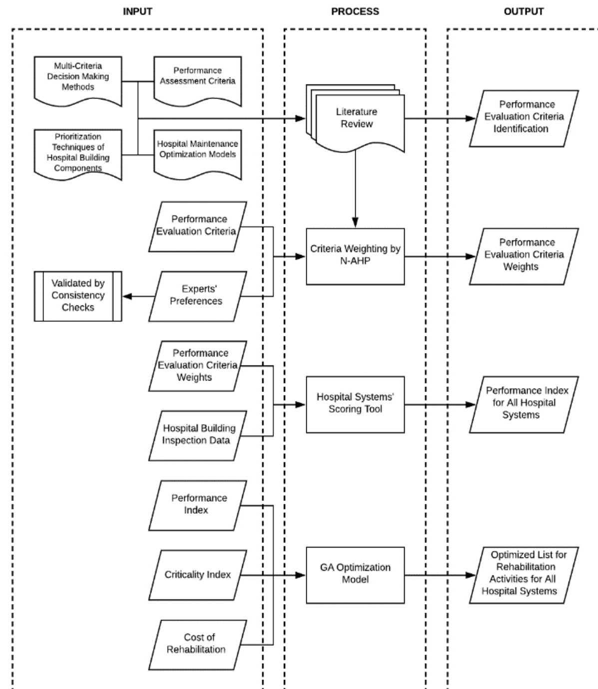

Fig. 1. Research Methodology Inputs, Processes and Outputs

The methodology adopted as part of this study and shown in Figure 1 starts with an extensive literature review on all the previous researches conducted on the areas of performance assessment, prioritization, as well as maintenance multi-criteria decision-making and optimization of healthcare facilities to outline the gaps and limitations of the previous models, and accordingly results in the identification of the performance evaluation criteria to be utilized in this framework. After that, a survey questionnaire was developed to gather the experts' preferences and feedback regarding the weighting of the identified criteria, and their opinions were analyzed using the N-AHP weighting scheme developed to get the final breakdown of the criteria weights. The weights were then entered into the scoring tool along with the gathered inspection data from an actual hospital to derive the performance index for each hospital building system, and this was then input to the optimization model with the rehabilitation cost and criticality values to formulate the optimization objective that will create the improved renewals list based on the input objectives and applied constraints.

A. Evaluation Criteria Identification

For the purpose of creating a comprehensive performance assessment framework for hospital building elements, the most important criteria for evaluation have been identified which are: 1) Physical Condition, 2) Code Compliance, 3) Sustainability Level, and 4) Capacity Appropriateness. The physical condition is the level of defects observable within the component upon visual inspection or non-destructive testing. In this paper, the rating scale utilized for this criterion follows a 6-point scale representing condition levels ranging from an Excellent to a

Critical condition. Code compliance on the other hand is the agreement of the current system configuration and usage with the current or future code requirements which is rated on a three-point scale where the highest score is given to components meeting the current and/or the future code requirements, while the lowest score is given for components that do not comply with the current code requirements and accordingly require a major upgrade. The sustainability criterion evaluates the current state of the energy and water efficiency within the operation of the component being studied. While capacity appropriateness is a measure of the adequacy of the component sizing in order to serve and maintain the current and seasonal operational conditions within the facility. To evaluate the previously identified criteria, visual assessment has been selected as part of this research due to its ability to deliver an adequate level of detail for renewal purposes [7] and [8]. However, the breakdown of the relative importance of each of the identified criteria is variable depending on the component being studied. Also, the Criticality Index calculated in the study by [12] was used in this model to prioritize the components under assessment. As part of this study, a complete case study hospital was considered with all its available systems accounted for. Therefore, more than one cycle of interviews with experts in the field of maintenance and repair of hospital building components have been held in order to rate the importance of each criterion with respect to the different systems and subsystems on a basis of an integration between Neutrosophic Logic and Analytic Hierarchy Process as described in the upcoming sections.

B. *Criteria Importance Analysis*

In order to create a unified Performance Index that incorporates the previously mentioned parameters, relative importance of the different criteria had to be analyzed with respect to each individual component group in the hospital setting. Experts were invited to rate the appropriate weight for each evaluation criterion on a basis of a pair-wise comparison in order to arrive at the relative weight of each criterion in producing the performance index. The Analytic Hierarchy Process was selected as part of this study to facilitate the multi-criteria assessment and analysis in a timely manner, and Neutrosophic logic was integrated to the AHP analysis to overcome the uncertainties, vagueness, and indeterminacies pertaining to human decision-making. The steps followed to apply the N-AHP methodology are demonstrated below.

Step 1: Developing the problem hierarchy in which the goal and criteria were identified with the purpose of creating the pair-wise comparison matrices to derive criteria weights.

Step 2: Converting the crisp weighting given by the experts into a Neutrosophic-based number consisting of a degree of truth, a degree of indeterminacy and a degree of falseness.

Step 3: Checking the consistency of the expert responses by using the following formulas adopted from [13] for the three cases possible to create a perfectly consistent neutrosophic matrix (T'ik , I'ik, F'ik), compare it with the actual responses and thus discard those not proved consistent.

- If k = i+1, then Mik = (Tik, Iik, Fik), and j = i+1

where Mik is the term describing a perfectly consistent preference relation with three neutrosophic components representing the degrees of: Truth, Inconsistency, and Falseness).

- If k > i+1, then Mik = (T'ik, I'ik, F'ik), and j = i+1; where T'ik, I'ik, F'ik can substitute the V'ik in the following equation:

$$V'ik = \frac{\sqrt{Vij * Vjk * Vik\text{-}1 * Vk\text{-}1k}}{\sqrt{Vij * Vjk * Vik\text{-}1 * Vk\text{-}1k} + \sqrt{(1\text{-}Vij) * (1\text{-}Vjk) * (1\text{-}Vik\text{-}1) * (1\text{-}Vk\text{-}1k)}} \tag{1}$$

where V' and V can substitute either T' and T, I' and I or F' and F respectively; and i, j, and k are indicators of the position of the term being studied inside the pairwise comparison matrix.

- If k < i, then Mik = (F'ik, 1 – I'ik, T'ik), and j = i+1

Based on the result of previous cases and equations, a consistency ratio is to be calculated as a last stage using the following equation:

$$\text{Consistency Ratio (CR)} = \frac{1}{2(n\text{-}1)(n\text{-}2)} \sum_{i=1}^{n} \sum_{k=1}^{n} \left(|T'ik\text{-}Tik| + |I'ik\text{-}Iik| + |F'ik\text{-}Fik|\right) \tag{2}$$

Step 4: Aggregating the experts' responses into one group decision-making matrix by using the following formulas [14].

For Aj (j=1, 2, 3, … n):

$$Yw = \left(1\text{-}\prod_{j=1}^{n} (1\text{-}TAj)^{wj}, 1\text{-}\prod_{j=1}^{n} (1\text{-}IAj)^{wj}, 1\text{-}\prod_{j=1}^{n} (1\text{-}FAj)^{wj}\right) \tag{3}$$

where j represents the experts' counter; w = (w_1, w_2, w_3, …w_n) is the weight vector of experts respectively; and $\sum_{j=1}^{n} wj = 1$

Step 5: De-neutrosophying the weights obtained consisting of three components, into a single crisp number Wc using the following equation [15].

$$Wc = \frac{3 + Ti - 2Ii - Fi}{4} \tag{4}$$

C. *Performance Scoring Tool*

After obtaining the weights of the criteria identified for rating the performance level of hospital systems, an automated performance scoring tool was developed as part of this study to facilitate the implementation of the developed framework by means of a simple straightforward scoring sheet that takes the input from the users regarding the assessment and inspection results for each identified criterion for a specific hospital system, and the tool automatically calculates the final integrated performance index to be used in further planning stages. This process is conducted as per Figure 2, where a sample scoring sheet is illustrated to provide an understanding of the tool.

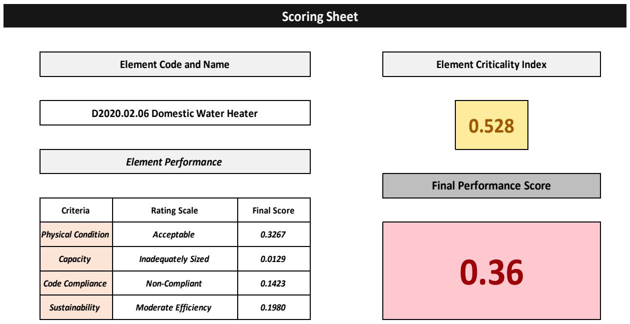

Fig. 2. Automated Performance Scoring Tool

The criticality index shown in the previous figure is obtained by following the approach presented in the study by [12] to prioritize hospital building systems according to their associated risks and criticality levels. As shown in the figure, even though the water heater has an acceptable physical condition which could have been sufficient for it to be omitted from the renewal planning process as per the current practice in Canadian hospitals, other functionality parameters showed an inadequate performance capability for this component which is the contribution of this study, and as thus, a high renewal likelihood can be forecasted for this building component as per the renewal optimization model.

D. Renewal Optimization Model

The optimization model developed in this study utilizes a Genetic Algorithm for conducting the optimization process due to its proven flexibility and capability of handling large scale problems with a big number of decision combinations to arrive at a near-optimum solution. The problem included in the model developed has passed several stages of design and formulations to reach the current goal. First, we explored an objective of maximizing the number of hospital systems experiencing a change in their performance in the year studied with a predefined budget allowance, and another objective of minimizing the amount of money spent on rehabilitation with a minimum improved performance level. However, we finally settled with a goal that combines the previous two functions while allowing for increasing the change observed in the most critical hospital systems' performance, as well as an efficient use of the budget available as a constraint. The final developed goal aims at maximizing the criticality weighted performance change per dollar spent on rehabilitation activities as shown in the equation below.

$$\text{Objective: Maximize } \frac{\sum_{i=1}^{n} C_i \left(P_{i\,new} - P_{i\,old}\right)}{\text{Total Cost}} \tag{5}$$

where Ci is the criticality index of system i, Pi new is the new calculated performance score of system i after the rehabilitation activity, Pi old is the initial performance state of the system, and the Total Cost is an accumulation of the budget spent on all rehabilitation activities inside the hospital building.

As part of this model, the decision variables are the rehabilitation options available for the hospital building systems, the constraints include a maximum budget to be set by the facility manager or the decision-maker in general to be able to track and monitor the expenditure inside the facility, and another constraint is that only one rehabilitation activity is allowed per building system to make the number of possibilities more realistic and applicable.

IV. Implementation

The methodology proposed in this paper was verified by means of application on a case-study hospital to demonstrate the capabilities of the developed models. The hospital selected for the validation purposes is a children's hospital in Western Canada constructed in 1970 as a three-story structure with a gross area of 9,355 squared-meters. The relevant data were gathered from the hospital inspection and audit reports on the physical condition observable within the building systems, as well as reports on code violation incidents, efficiency simulation results, and feedback from hospital personnel on capacity appropriateness of the various systems for the years 2016 and 2017 upon inspections carried out by specialized personnel. The collected datasets were used in calculating the performance indices of the systems as well as deriving their relative criticality indices for the purpose of prioritizing the systems' importance through weighing the consequences of failure and mission dependability levels of every system to be able to select the most suitable renewal activities to be implemented within a predetermined planning horizon. A sample of the calculated indices for hospital systems is given in the following figure.

System Code	Description	Criticality Index	Performance Index (Original)	Rehabilitation Action		Performance Index (Modified)	Cumulative Cost	Criticality-Weighted Performance Change
				Type	Cost			
D1010.01.02	Hydraulic Passenger Elevators	0.7841	0.5627	3	175,000	0.8192	1,043,000	3.21392
D2010.06	Bathtubs	0.2589	0.8726	0	-	0.8726	1,043,000	3.21392
D2010.08	Drinking Fountains/Coolers	0.3182	0.6239	0	-	0.6239	1,043,000	3.21392
D2020.01.01	Pipes and Tubes: Domestic Water	0.7699	0.5388	4	389,000	0.9526	1,432,000	3.53251
D2020.01.02	Valves: Domestic Water	0.4073	0.1218	3	140,000	0.7993	1,572,000	3.80845
D2020.01.03	Piping Specialties (Backflow Preventers)	0.4985	0.3479	1	55,000	0.4985	1,627,000	3.88353
D2020.02.02	Plumbing Pumps: Domestic Water	0.6249	0.7122	2	98,950	0.9891	1,725,950	4.05656
D2020.02.06	Domestic Water Heaters	0.8153	0.4608	4	45,000	0.9975	1,770,950	4.49413
D2030.01	Waste and Vent Piping	0.4118	0.5009	2	190,000	0.7105	1,960,950	4.58045
D2090.11	Oxygen Gas System	0.6902	0.4107	3	45,000	0.7883	2,005,950	4.84107
D2090.13	Vaccum Systems (Medical and Lab)	0.7127	0.5623	3	60,000	0.8192	2,065,950	5.02416

Fig. 3. A snapshot of the calculation procedure followed as part of the optimization model

The optimization method was then validated by means of a comparison between the results obtained from our developed model, with the actual results extracted from the datasets for the year 2017. To start with, criticality and performance indices were calculated for the years 2016 and 2017. Then, the accumulated cost and criticality-weighted performance improvement was determined for the year 2016 after implementing the optimization model and selecting the best rehabilitation strategies to be implemented for every hospital system. After that, using the actual data from the year 2017, the cost spent on rehabilitation was summed up as well as the criticality-weighted performance improvement corresponding to the rehabilitation actions already implemented on site. By observing the differences between the two procedures demonstrated in Table 1, our model has shown a better and more economical performance enhancement for the hospital critical systems than actually implemented hospital rehabilitation actions. Based on the improvement in the criticality-weighted performances and the total budgets spent on rehabilitation in both cases, our model presented a 34% improvement in the change experienced within hospital systems per dollars spent on rehabilitation. This is further illustrated in the following table.

TABLE I. COMPARISON BETWEEN RESULTS OF THE DEVELOPED MODEL AND THE ACTUAL HOSPITAL

Comparison Parameters	Calculated	Actual
Criticality-Weighted Performance Change	13.4733	10.1829
Total Rehabilitation Cost	2,898,450	2,938,500
Criticality-Weighted Performance Change Per Total Cost*10^5	0.4648	0.3465

V. CONCLUSION

The continuous deterioration of hospital assets coupled with the insufficient funding spent on hospitals' rehabilitation are two of the main drivers of the escalated amounts of operational failures and interruptions in hospital buildings in Canada. Therefore, this paper was articulated with the goal of creating a prioritization framework for hospital building systems as well as a performance evaluation tool to assist decision-makers in making efficient decisions regarding rehabilitation activities and fund allocation. In addition to that, an optimization model was developed to select the most suitable rehabilitation action to be applied for hospital systems in order to result in an improved overall performance change per dollar spent on rehabilitation. The results attained from the developed model was compared to a case-study hospital where actual rehabilitation actions were undertaken, and the improvement in performance was calculated for both cases where the developed model outperformed the current practice with 34%. This validates the developed model and suggests that it can be used by facility managers and decision-makers to allocate the rehabilitation budgets to the most critical areas in the hospital building.

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