CRITICALITY-BASED MODEL FOR REHABILITATING SUBWAY STATIONS

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ABSTRACT

According to the Canadian Urban Transit Association (CUTA), 140 Billion CAD is required to maintain, rehabilitate, and replace subway infrastructure between 2010 and 2014. The current practice adopted by transit authorities for prioritizing subway stations for rehabilitation is based on the station structural needs. While this classification is reflective of station condition, other factors, such as station size, location and passenger capacity, play an important role. The criticality of a station is an index that represents the functional importance of a station depending upon a set of identified factors. The system criticality is based on several attributes, such as station location, size, and nature of use. This paper presents a novel method of clustering subway stations for rehabilitation priority based on their criticality level. The different stations in a subway network are rated according to their relative importance against predefined attributes. The weights and scores of the attributes are computed with the help of experts and current subway network data. The analysis is done using the Fuzzy Analytic Network Process (FANP) to accommodate the subjectivity of human judgment as being expressed in natural language which entails 'fuzziness' in real-life problems and account for the interdependency between the selected attributes. The output of the model is a criticality based clustering of subway stations. The proposed framework helps authorities prioritize stations for rehabilitation and highlight stations with more criticality for a more robust asset analysis.

KEYWORDS

Subway stations, criticality Index, Fuzzy Analytic Network Process, Fuzzy Preference Programming.

INTRODUCTION

Subway systems represent a class of safety-critical assets. The Montréal metro, operated by the Société de transport de Montréal (STM), is considered one of the safest and oldest in North America. It has been an integral part of Montreal's life for more than 35 years, covering a total operational length of 60.5 km. As stated by the historian Jean-Claude German, "The metro is for Montreal what the boulevards are for Paris or the canals for Venice." However, the stations are constantly deteriorating due to their age and excessive passengers use. According to Semaan (2011), (STM) has estimated the improvement value of its network to be 493 million CAD in 2007. Moreover, it estimated a required amount of 5.1 Billion CAD for the maintenance of the subway system infrastructure for the next ten years. Nonetheless, STM is faced by the problem common to all public authorities that is lack of fund. This prevents addressing all the rehabilitation needs of the different systems in a timely manner. Different metro stations pose different rehabilitation and maintenance needs based on their location criticality and the frequency of passengers using the stations. Several research attempts were done to prioritize stations for rehabilitation based on condition assessment or deterioration models. Nevertheless, these models neglected the relative importance of individual stations derived from their unique characteristics. This research presents a novel stations ranking method according to the criticality level of each station, which is an important aspect in selecting the station priority for rehabilitation in real-life.

BACKGROUND

The Criticality Measures

Carretero et al. (2003) applied the Reliability Centered Maintenance (RCM) methodology in railway infrastructures through the project “RAIL: Reliability centered maintenance Approach for the Infrastructure and Logistics of railway operation”. In this project, the criticality of a system was introduced as the measure of a system importance from a functional point of view. They computed criticality by means of a set of factors identified by a team of RCM experts, railway maintenance engineers, and railway managers, hence, the criticality score is the summation of the values of all factors. The criticality factors included (i) technology, being mechanic, electro-mechanic, electric or electronic, (ii) Traffic density measured as the number of circulations per day, (iii) Revenues obtained from exploitation, (iv) line availability, and (v) environmental and safety risk. On the other hand, (Gonzalez et al. 2006) computed criticality for different systems in a railway network and used it as a base to rank machines and classify them according to their importance for the whole network. They defined a set of factors to measure criticality and computed it as an addition of weighted factors values. The criticality conveyed the ranking of the functional importance of each component of the infrastructure, including lines, sections, and systems. In the Risk-Based Inventory Management System (RIMS) prepared and applied by the City of Edmonton, a “severity” indicator was defined. This indicator provides an analysis of expected assets in critical condition and the impact of failure of those assets (Leeman 2010). The different methods to compute criticality or severity basically reflect the importance of a systems’s components in terms of their functionality and importance in delivering the final service or product. However, through consulting the literature on subway stations, no effort was documented to measure the criticality of metro stations or to classify stations other than on a structural basis. Abu-Mallouh (1999), Farran (2009), Semaan (2009), and, Semaan (2011) did considerable efforts in assessing the stations’ condition through diagnostic models such as condition assessment and deterioration models. Nevertheless, all these models studied the system from a structural point of view only without considering the functional aspects of the system. This triggered the current research to try to introduce the concept of criticality into the subway system.

The Fuzzy Analytic Network Process (FANP)

Saaty (2005) developed the Analytic Network Process (ANP) as an extension to AHP problems with criteria dependencies and feedback. The AHP/ANP framework is characterized by three basic features that make them useful in multi-criteria decision-making problems. First, modeling the system’s complexity using a network or for more specific cases, a hierarchy. Second, measuring on a ration scale that ensures simplicity, and last, synthesizing to obtain the results. The fundamental scale for pairwise comparison in the ANP builds upon two main questions; (1) which of two elements is more dominant with respect to a given control criterion, and (2) which of two elements influences a third element more with respect to the control criterion. The comparison is conducted to express the qualitative judgments between criteria numerically. Garuti and Sandoval (2005) reported that ANP provides a way to clear all relationships among variables, and thus, decreases significantly the breach between model and reality.

Nevertheless, the ANP-based decision model is noticeably ineffective when dealing with the inherent fuzziness or uncertainty in judgment during the pairwise comparison process. Using a discrete scale to represent the verbal judgment does not account for the uncertainty and imprecision associated with mapping a person’s judgment to a crisp number (Kahraman et al. 2006). Promentilla et al. (2008) stated that in real-life decision-making situation, the decision makers/experts could be uncertain about their own preference level, due to insufficient knowledge, lack of appropriate measurement scale or, uncertainty within the decision environment. In addition, decision makers tend to specify preferences in the form of natural language expressions that are most often vague and uncertain. Fuzzy logic is a natural way to incorporate the vagueness of the human judgment through using the Fuzzy Analytic Network Process (FANP). When comparing two elements, the uncertain numerical ratio is expressed in a fuzzy manner rather than an exact one. Then, an appropriate prioritization procedure is applied to derive local priorities that satisfy the provided judgments. Mikhailov & Singh, (1999) (2003) proposed the Fuzzy Preference Programming (FPP) technique to derive crisp priorities from interval and fuzzy judgments. The supermatrix priority-derivation process in the ANP entitles complex matrix operations on real numbers; therefore, the most practical approach for incorporating the fuzzy concept into the ANP framework is by deriving crisp weights from the fuzzy comparison matrices. The FPP provides an appropriate index to measure the inconsistency of human judgments especially when the decision maker's performance is strongly inconsistent (Yu et al. 2007). FPP adequately represents the initial fuzzy sets by adopting the concept of α–cuts to decompose fuzzy numbers into a number of intervals, which are further aggregated into crisp priorities (Mikhailov 2003).

Based upon the literature review, the concept of criticality was previously utilized for classification and ranking especially for equipments, the concept was broadened in the RAIL project to be applied to railway networks still in an equipment wise scope through considering signalizing devices, track circuits, and signals. However, this concept has not been introduced yet in the area of subway networks. Through consulting the literature on the criticality measures, the concept of criticality proved successful when applied for classification based on the functionality level. On the other hand, the available models in the area of subway networks focused only on the structural view of the stations and neither of the developed models approached the stations ranking from a functional point of view. This triggered the current research to identify and search for the factors contributing to an increased criticality level of a subway network and develop a model for clustering the network accordingly. The model is designed not to be time consuming or difficult to implement, but rather simple and practical for the analysis of a citywide subway network based on the criticality level.

RESEARCH METHODOLOGY

This research introduces the concept of criticality for the scope of subway networks as the criticality index. First, the research breaks down the subway network into building blocks of systems and subsystems to facilitate studying the criticality level. This resulted in the subway breakdown structure shown in Figure 1. Second, each level of the breakdown structure is studied to select the most suitable element for use in the criticality calculations. The element is selected such that its criticality level is dominant and diverse enough to prevail over other network components. Consequently, subway stations are selected to be the focus of the criticality analysis. Systems and subsystems share the same major role of delivering the service; however, their criticality is derived from their respective locations in stations that vary in criticality according to several factors. From this discussion, the concept of criticality propagation is introduced; the criticality level propagates upwards and downwards in a hierarchy of a subway network such that systems and subsystems acquire the same criticality level as the stations where they operate. Similarly, a line criticality is computed as the sum of criticality indices of stations existing on this line. For interconnecting systems such as tunnels and auxiliary structures, the criticality level is computed as the higher index of the two corresponding stations through which this system connects.

After breaking down the infrastructure system to pinpoint its critically active component. The research then proceeded to identify and define the factors contributing to an increased station criticality. The Montréal metro is used as an example to highlight factors contributing to station criticality, through analyzing the network in accordance with the criticality calculations. During the analysis, the differences between metro stations are highlighted and the factors affecting a station criticality are then extracted for further analysis and model development. The factors contributing to the station criticality index are identified through historical data, expert opinion and by consulting the current structure and map of the Montréal subway network, as shown in Table 1. The station criticality is a complex decision based on different attributes defined as; number of lines, number of levels, station use whether end or intermodal, and station proximity to different attraction locations. The criticality factors defining a station differ in significance, thus, the authors introduced a weight component in the criticality index equation to accommodate the subjective variability in the attributes weight. While weights of different attributes are constant for all stations across the network, the score of each attribute is station-dependent; it can be seen as a scale from less to more critical. The attribute scores are computed based upon the network under examination and individual station information, as shown in Table 1. Expert judgment, on the other hand, will be used to obtain the weight of different attributes.

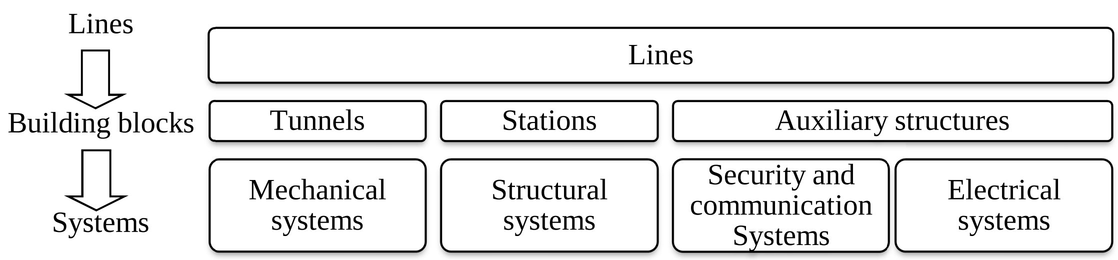

Figure 1-Subway breakdown structure

Station criticality is defined in terms of three main factors and seven sub factors or attributes. Amongst attributes identified, the station location is the most diverse. The Montréal metro has 68 stations spreading on four lines of metro and covering the north, east, and centre of the Island of Montreal with connections to Longueil, and Laval. Accordingly, the Montréal subway map was studied in depth to identify all the possible points of interest accessible by a metro station or a bus from a metro station. The points of interest were then grouped based on their relevance into three groups of locations; recreational, residence, or, vitalities. Table 2 lists the full description of existing attraction types, points of interest and their grouping. Once criticality score is computed for the stations under study, they can be further classified based on their importance with respect to the network. The classification method relies upon the criticality index identified as the functional role a station plays in its location.

Table 1-Criticality factors definition and scores

Factors	Attribute	Definition	Score
Station Size	# levels	The increased number of levels reflects an increase in expected passenger capacity	Normalized, based on the maximum number of levels as defined for the network under study
	# lines	The increased number of lines reflects an increase in expected passenger capacity	Normalized, based on the maximum number of lines as defined for the network under study
Station Nature of Used	Intermodal	Intermodal stations pose a greater importance since a higher passenger frequency is expected.	Computed as binary value, (1) for an intermodal station and (0) if else
	End station	End stations work as collector stations where a higher passenger frequency is expected.	Computed as binary value, (1) for an end station and (0) if else
Station Location	Recreational Residence Vitalities	Stations pose higher criticality due to their proximity to high passenger frequency locations.	Computed as a binary value ;(1) for stations in a high capacity location and (0) if else. Intermediate values for medium locations.

Table 2-Attractions definition by group

Attraction type	Points of Interest	Group
Main Touristic Attractions	Museums, Theatres, Centre Infotouriste, Old Montreal, Old Port, Palais des Congrès de Montréal, Parks, Historical Sites, Squares, Malls and, shopping Centers	Recreational
Sports	Arenas, Stadium, Clubs	
Culture	China Town, Cinemas, Libraries, Cemetery	
Transportation	Central Bus Station, inter-city rail station	Vitalities
Businesses	Locations for Commerce Chambers, Quartier International de Montréal	
Worship Places	Churches, Mosques, Temples, Cathedral, Oratory	
Educational	Schools, Universities, Colleges	
Governmental	City Hall, Court	
Health Care	Hospitals, CLSC's, Health Institutes	
Residence	Areas of high, medium, and low residence	Residence

The station criticality attributes are strongly connected, hence, cause and effects loops flow between them. Therefore, the FANP is used to compute the attributes weight. The Criticality Index model is outlined in Figure 2. The following steps summarize the criticality-model steps;

1) Determine criteria and sub-criteria weight (CRw_i) through the FANP with application to the FPP;
    i. Decompose the decision problem to a network of clusters and criteria as nodes and sub nodes.
    ii. Construct pairwise comparison matrices of the components with fuzzy ratio judgments. The fuzzy extension of the 9-point fundamental scale proposed by Saaty (2001) and shown in Table 3 is used. Triangular fuzzy numbers are selected for their wide applicability and ease of comprehend by decision makers.
    iii. Perform FPP method on each comparison matrix individually to derive sets of local priorities. Calculate the weights using the FPP method according to equation 1. It is required to derive crisp priority vector $w = (w_1, w_2 \dots w_n)^T$, such that the priority ratios w_i/w_j are approximately within the scopes of the initial fuzzy linguistic judgments provided,

$$\text{Max } \lambda \tag{1}$$
$$\text{Subject to} \quad (m_{ij} - L_{ij})\,\lambda w_j - W_i + L_{ij}W_j \leq 0$$
$$(u_{ij} - m_{ij})\,\lambda w_j + W_i - u_{ij}W_j \leq 0$$
$$i = 1, 2, 3, \dots, n\text{-}1, \qquad j = 2, 3, \dots, n, \qquad j>i$$

    Where;
    L_{ij}, m_{ij}, u_{ij} are the lower, medium, and, upper bounds of the triangular judgments respectively.
    MATLAB® is used at this stage of the analysis due to its known capabilities for solving non-linear equations. The output of this step is crisp weights derived from fuzzy judgments.
    iv. Develop the unweighted super matrix based on the interdependencies defined and the crisp weights obtained from step iii.
    v. Develop the weighted supermatrix by adjusting the unweighted supermatrix to column stochastic.
    vi. Find the limit supermatrix with a sufficiently large power to converge into a stable supermatrix.
    vii. Steps (iv) to (vi) are done with the Super Decisions® Software developed by Saaty (2012). The expected output from these steps is global and local weights of criteria and sub criteria.
    viii. Obtain the final priorities via aggregating the weights of criteria and the scores of alternatives.
2) Determine Criticality score (CRsI) per station using actual station location and data to assign scores.
3) Compute the total Criticality Index per station ($C_R I_i$) using equation 2,

$$C_R I_i = \sum_{i=1}^{n} CRwi * CRsI \quad (2)$$
i=1,2, …,n, n= criticality attributes

4) Classify stations based on their criticality Index level ($C_R I_i$).

Table 3-Saaty Linguistic scale of relative importance

Linguistic Scale used	Triangular fuzzy scale
Equal Importance	(1,1,1)
Moderate Importance	(2,3,4)
Strong Importance	(4,5,6)
Very strong Importance	(6,7,8)
Absolute Importance	(9,9,9)

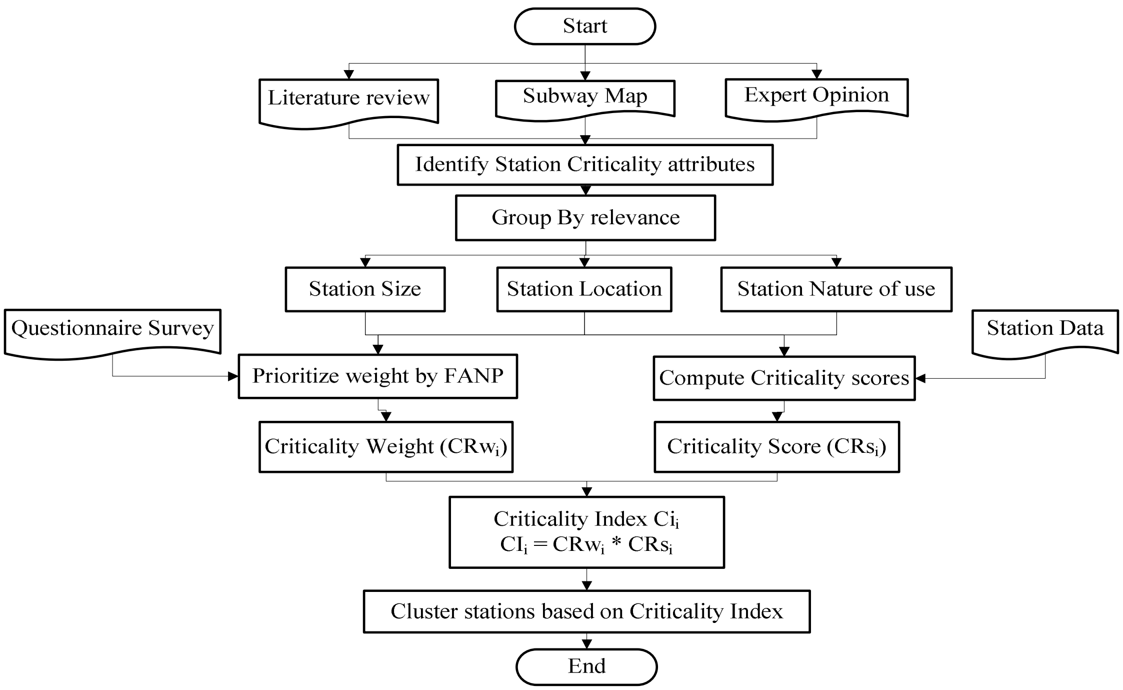

Figure 2-Criticality Index Model outline

ILLUSTRATIVE EXAMPLE

To validate the model, questionnaire surveys were distributed among subway managers to obtain the required inputs of scores and weights. However, none of them has been yet received. Therefore, the potential benefits of the proposed methodology are demonstrated using an illustrative example. The criticality index is calculated across three subway stations to categorize them accordingly. Hypothetical weights for the criticality attributes are assumed whereas the scores are computed from actual station data of the Montreal subway. Stations are given arbitrary names A, B, and C. Station A is a connection station with multiple lines and levels. Where, B and C are one-level stations, with B located in downtown and C as an intermodal station. Following the steps outlined in the methodology, the global and local weights of the criteria and attributes are computed as shown in Table 4. Next, scores are calculated based on actual station data. Finally, equation 2 is used to calculate the criticality scores per station. Table 5 presents example calculations for criticality scores and indices per station.

Table 4-Example of local and global weights obtained using ANP

Main Criteria	Global weight	Attributes	Local weight	Global weight
Station Size	35.6%	# Levels	24.70%	8.79%
		# lines	75.30%	26.81%
Station Nature of use	26.2%	Intermodal	56.80%	14.88%
		End	43.20%	11.32%
Station Location	38.2%	Vitalities	35.30%	13.48%
		Recreational	32.60%	12.45%
		Residence	32.10%	12.26%

Table 5-Example of criticality scores and indices calculations

Attributes	W_{Global}	Station A		Station B		Station C	
		(CRs_I)	$(C_R I_i)$	(CRs_I)	$(C_R I_i)$	(CRs_I)	$(C_R I_i)$
# Levels	8.79%	1	0.0879	0.33	0.029	0.33	0.029
# lines	26.81%	1	0.2681	0.33	0.088	0.33	0.088
Intermodal	14.88%	0	0	0	0.000	1	0.149
End	11.32%	0	0	0	0.000	0	0.000
Vitalities	13.48%	1	0.1348	1	0.135	0.8	0.108
Recreational	12.45%	1	0.1245	0	0.000	0	0.000
Residence	12.26%	0.8	0.09808	0.6	0.074	0.3	0.037
$\sum$	100.00%		0.71338		0.326		0.411

The proposed model compares between stations on a criticality basis, it proved station A to be the most critical followed by stations C then B. This conforms to the nature of station A as having the maximum number of lines and levels in the network. It also ranked station C as more critical although station B falls in the downtown in proximity to higher vitalities and residence. This is because of the nature of station C as an intermodal station. The model provides a functional level of stations analysis in a quick and easy to comprehend framework that is not complex or time consuming. This analysis level provides insights to the passenger and proximities requirements when ranking stations for rehabilitation and adds a level of detail and a new dimension of functionality, which are usually neglected in stations ranking.

CONCLUSION

The current paper presents a criticality-based model for clustering subway stations. Models developed in subway area depend upon the structural classification while neglecting the functional aspects of the network. This model presents a found methodology for a network ranking based on the functional importance of its stations. The presented model studied the Montreal subway network from a functional point of view and identified factors contributing to an increased station criticality. The analysis utilized the FANP to account for the cause and effects loops flowing in between criticality attributes and account for the imprecision associated with mapping of an expert's judgment. An illustrative example is presented to demonstrate the use of the model and validate its use for criticality-based stations classification. The model ranked three different stations with different characteristics and proved to avoid complex calculations and excessive time consumption. The developed model offers a framework for clustering subway stations based on a functional view of criticality, which adds to the structural clustering of subway stations. This methodology opens new horizons for ranking stations for rehabilitations while considering the passengers frequency and customers' needs. It should be noted that the benefits realized from a structural classification are numerous; therefore, the extension of this research will work on integrating the structural-based classification with the proposed functional based classification to provide a comprehensive subway network classification. For future research, the proposed methodology will be applied in real case studies for reliability and validation matters and integrated to the appropriate structural assessment classification method. .

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