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Multiple perspective consequence of failure estimation of subway stations

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Abstract: According to the Canadian Urban Transit Association (CUTA), the capital infrastructure needs for the period (2012-2016) are estimated at 53.5 billion CAD from which 40 Billion CAD only can be met by existing programs whereas a shortage of 13.5 billion CAD exists. The subway maintenance process is usually constrained by fund scarcity, which calls for a comprehensive prioritization method. The current practice adopted by most transit authorities prioritizes elements per station for rehabilitation based on the structural performance only while neglecting consequences of failure despite being crucial in ranking stations for rehabilitation. This paper presents a qualitative multi-perspective consequence of failure estimation model for subway metro stations. Consequences of failure are identified and assessed on multiple perspectives, namely; financial, operational, and social impacts of failure. The research revealed that the expected consequences of failure are interdependent and strongly connected; hence, the Fuzzy Analytic Network Process (FANP) is used with application to the Fuzzy Preference Programming (FPP) method. The FANP accommodates the subjectivity of human judgment as being expressed in natural language which entails 'fuzziness' in real-life problems and accounts for the interdependency between the selected attributes. The developed model offers a framework for clustering subway stations according to the expected consequences of failure severity for element level and station level. An illustrative example is presented to validate the model and prove its robustness. The proposed framework helps authorities prioritize stations and elements along stations for rehabilitation and highlights stations with more expected failure consequences for a more comprehensive asset analysis.

1. Introduction

Subway systems are essential public transit assets and one of the safest modes of transportation. They represent a class of safety-critical assets that should be studied in depth since their failure has catastrophic consequences like multiple fatalities or injuries, partial or complete loss of service, major traffic disruptions, and different socio-economic effects. A subway network is typically composed of diverse components and systems operating simultaneously to deliver the required service. This component diversity causes a level of complexity that complicates the process of assessing and maintaining the network at the desired level of service. In addition, the problem of fund scarcity faced by most public authorities converts it into a tough task. According to Semaan (2011), the "Société de Transport de Montréal' (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. However, 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 systems operating in a subway network are competing for rehabilitation priorities while having various consequences of failure (CoF) and multiple failure modes. This turns the prioritization process into a tough task. Elements operating in a subway network pose diverse rehabilitation and maintenance needs based on their role in the network hierarchy and the operation. Several research attempts were done to prioritize stations for rehabilitation based on condition assessment or deterioration models. However, these models neglected the expected consequences of failure whether tangible (material, labor, equipment) or intangible (loss of service, socio-economic costs). Such information cannot be captured by the conventional condition ratings, which is the practice adopted by most transit authorities. This research presents a novel methodology for the consequence of failure estimation in subway networks from multiple perspectives. The research goes beyond just the monetary CoF to estimate subjective consequences such as operational and social effects.

2. Background

2.1 Consequences of Failure (CoF)

The importance of determining the consequences of failure cannot be over emphasized; a formal review of such consequences diverts attention away from maintenance tasks having little or no effects and focuses on more-effective maintenance tasks. This ensures optimizing the maintenance spending and guarantees the inherent reliability of the equipment is enhanced (Gonzalez et al. 2006). Consequences of failure imply the various types of loss expected in case of loss of function. These losses are tangible; like repair cost, property damage, and, revenue loss. However, most of the expected consequences are mostly intangible such as service disruption, reliability loss, and, different social impacts. Researchers adopted diverse techniques for capturing the CoF expected for different infrastructures. The area of sewer and pipelines had the largest share of literature dedicated to estimating the consequences of failure. One of the most influential efforts for understanding and categorizing the CoF for pipelines was prepared by the United Kingdom's Water Research Center (WRC 1986). The CoF were assessed by considering the socioeconomic impacts and the reconstruction impacts. Socioeconomic impacts incorporate the threat to human health and environmental quality and the costs associated with a loss of commerce, critical services, and sewer service. Reconstruction impacts consider the costs to the sewer utility to repair or replace failed sewers. Hahn el al. (2002) used two mechanisms to predict the impacts of failure in his knowledge-based expert system based on the (WRC 1986) paradigm of assessing the pipes. Kleiner et al. (2004) developed a risk model for buried pipelines. In this model, CoF were measured on a fuzzy qualitative nine-grade scale from extremely low to extremely severe.

Baris (2010) developed a risk assessment model at an individual pipe level and estimated the CoF values by examining the geographical, physical, and functional attributes of sewer pipes in the light of expert opinions. Fares and Zayed (2010) followed a qualitative approach to quantify the CoF in their risk model for water main failure. The CoF measured the repair cost, traffic and business disruption, loss of production, and, type of service area. Seattle Public Utilities calculated the risk of failure in monetary terms through estimating the CoF as the multiplication of the base repair/replacement cost with modification factors based on the attributes of sewer pipes (Martin et al. 2007). Despite the numerous models for estimating the CoF discussed, the literature does not show much effort in the area of subway networks. 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. However, neither of these models studied the consequence of failure nor attempted to measure them. The consequence of failure estimation is characterized by a high level of uncertainty associated with determining the direct costs of rehabilitation or repair and even higher uncertainty and intangibility in determining the indirect costs such as social and operational costs.

2.2 The Fuzzy Analytic Network Process (FANP)

When the decision taken is one that involves uncertainty, complexity, as well as multiple and possibly conflicting criteria, the Multiple Criteria Decision Making (MCDM) tools are recognized as a valuable method to solve such problems. Saaty (2005) developed the analytic hierarchy process (AHP) as a multi-criteria decision support methodology. The Analytic Network Process (ANP) was later developed as an extension to the AHP problems with criteria dependencies and feedback. The ANP derives relative priority scales of absolute numbers from a group of judgments that represent the relative influence of one of two elements over the other in a pairwise comparison with respect to an underlying control criterion. 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 and 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 the 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 the relationships among variables, and thus, decreasing 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 in the pairwise comparisons has the advantage of being simple and straight forward, yet, it does not account for the uncertainty and imprecision associated with mapping a person's judgment to a crisp number and cannot reflect the human thinking style (Kahraman et al. 2006). Promentilla et al. (2008) stated that in real-life decision-making situation, the decision makers could be uncertain about their own preference level, due to incomplete information, 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 uncertainty and vagueness of the human judgment. 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 which derives 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 first deriving crisp weights/priorities from fuzzy comparison matrices. The FPP is applied to increase the ANP capabilities in dealing with inconsistent and uncertain judgments through considering crisp comparison judgments as interval judgments with equal lower and upper bounds. 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). Through adopting the concept of α–cuts to decompose fuzzy numbers into a number of intervals, the FPP adequately representing the initial fuzzy sets, which are further aggregated into crisp local and global priorities (Mikhailov 2003). The process of applying FANP using the FPP can be summarized in the following main steps:

- Decompose the decision problem to construct a hierarchical or network structure including clusters, criteria, sub criteria, lower elements, and alternatives.
- Highlight the dependences among all components and define the impact between each.
- Construct pairwise comparison matrices of the components with fuzzy ratio judgments.
- Perform FPP method on each comparison matrix individually to derive each set of local priorities.
- Develop the unweighted supermatrix with the derived local priorities from previous step.
- Develop the weighted supermatrix by adjusting the supermatrix to column stochastic.
- Find the limit supermatrix with a sufficiently large power to converge into a stable supermatrix.
- Obtain the final priorities via aggregating the weights of criteria and the scores of alternatives.

Based upon the literature review, it is obvious the problem of estimating the failure consequences for subway stations have been poorly, if ever, addressed in the literature. Failure consequences are difficult to estimate due to their diverse and intangible nature. The literature however provided methods for CoF estimation for other types of infrastructure like sewers and pipelines. Other than the direct costs of failure and repair, the expected indirect consequences are difficult to monetize and measure (Muhlbauer 2004). Therefore, the methodologies adopted were mainly qualitative and incorporated expert judgment for constructing a base of consequences estimation. The need for a methodology that estimates the multiple and diverse consequences of subway failure is crucial. The fuzzy ANP is suitable for the analysis since it incorporates the inherent impression and subjectivity of relying on a qualitative method for the CoF estimation and will help provide more realistic and robust results.

3. Research Methodology

The problem of estimating the consequences of failure presents a challenging problem to researchers and industry experts due to the uncertainties associated with the different failure impacts. Direct financial impacts of a subway element/station failure can be estimated in monetary terms based on historical data and inspection reports. The case for indirect failure impacts is different; calculating failure impacts for intangible factors in monetary terms is difficult and does not yield accurate results due to the high level of uncertainty and subjectivity associated with these factors. The indirect impacts of failure of subway station include, but are not limited to, service disruption, passenger delay, loss of reputation, loss of revenue in addition to other socio-economic impacts reflected as the extent to which the failure affects adjacent services and customers benefiting from the service and the ease of providing an alternative service. Estimating CoF for a subway network is of a highly valuable importance; it provides the public authorities with a framework for categorizing the network into groups of relative importance. However, in practice, only a fraction of the expected CoF can be monetized whereas most of the expected indirect failure costs are difficult to monetize and measure (Muhlbauer 2004). One way to overcome the difficulty inherent in these calculations is measuring the CoF using indices, which facilitates the comparison between the expected CoF and highlights areas of higher failure impacts. From this discussion, it is clear that the major purpose of identifying CoF in this research is to compare and rank station rather than estimate the actual cost of failure in monetary or exact terms. Thus, CoF are estimated using a relative measure of importance assigned to each element/station based on a set of carefully identified attributes.

The research started by conducting an extensive study to determine the factors affecting CoF calculations in terms of tangible and intangible failure impacts. This revealed a wide spectrum of consequences of failure occurring at two different levels, element and station level. A station is composed of a number of elements operating simultaneously. Based on the location of the element in the station and the nature of task the element performs, the element failure might cause total, partial, or no station closure. This suggests that the CoF are element-dependent, in addition, the station location is a strong factor of the analysis. According to the series-parallel reliability techniques, two outlines exist for an element's location in a station: in parallel or in series. A system in parallel is a redundant system where its elements work simultaneously, the system will fail if all elements of the system fail. On the other hand, a system in series requires all of its elements to operate to function effectively. A subway station is composed of elements operating in element, in series, or in a combination of both. For instance, the slab system is considered a redundant system that can operate even if one of its components fails; hence, it operates in parallel. Using this configuration, it can be concluded that (1) for failure in series systems, the entire floor is expected to fail and thus, total service disruption, and station-level closure is expected. (2) For failure in parallel systems, partial or no closure is expected, in case one or more element in a parallel system fails. In case all the elements composing a system fail, the system is not expected to operate and total system closure is expected.

CoF are studied from multiple perspectives to cover the potential expected failure impacts. Figure 1 outlines the CoF model. Based on literature and expert opinion, the CoF can be broadly grouped into financial impacts, social impacts, and operational impacts of failure. It is noted that some factors could fall under two different perspectives simultaneously.

Financial Impacts present the direct tangible costs of material, labor, and equipment. These costs are measured in terms of cost of maintenance, repair or, replacement of the failed component(s). In addition, the expected revenue loss due to the service interruption for repair actions is counted towards financial impacts. The service interruption depends upon the element configuration and the interruption rate whether none, partial, or total and are considered in the operational impacts.

Operational impacts are the consequences involving managerial decisions; they include time to repair and ease of providing alternative. The time to repair is the total time required to return the failed component into a functioning state. The ease of providing alternative is also a major concern since if an alternative is provided quickly and easily, the impact of failure can be minimized and the social costs incurred from this failure are kept to a minimum.

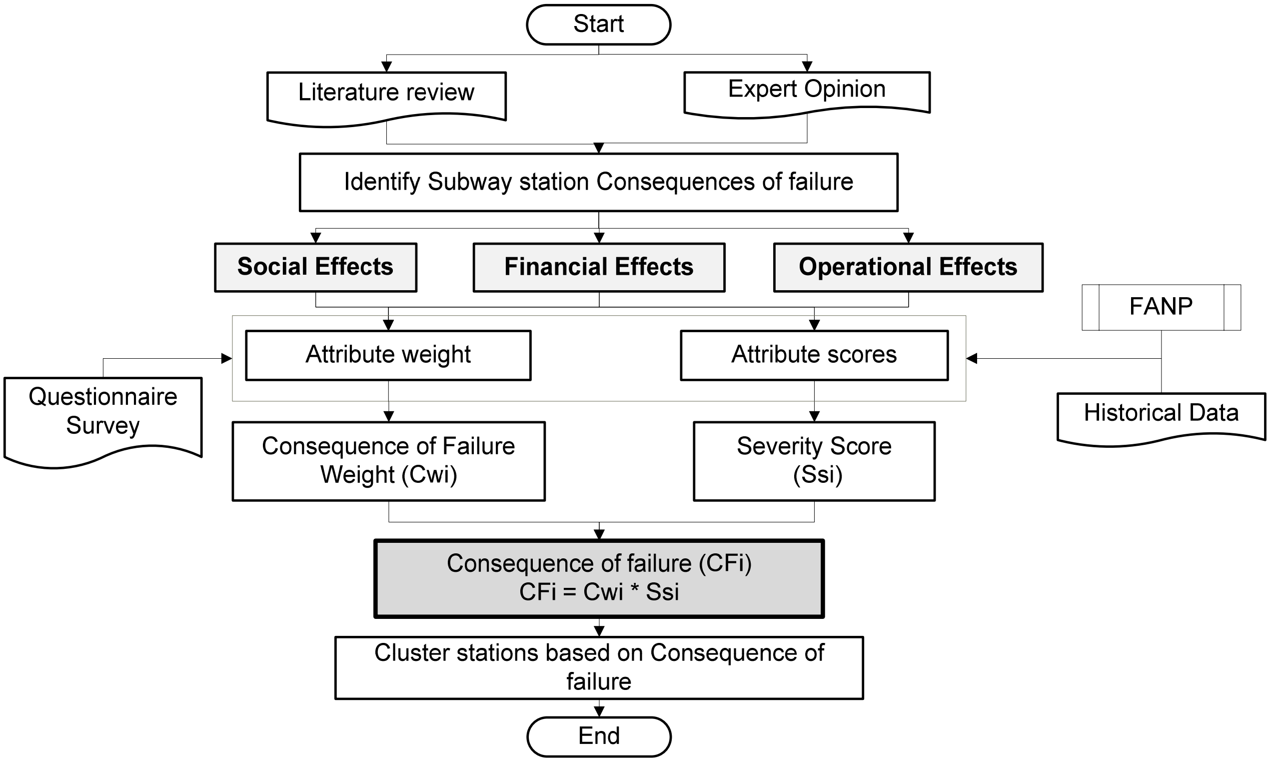

Figure 1: Consequences of failure model outline

Social impacts are the direct social consequences of failure incurred by the customers. They are measured in terms of number of users of the station and adjacent businesses, interruption rate, and degree of service interruption. The magnitude of the social impacts of failure is directly proportional to the number of users using this station and the adjacent businesses to which this station connects. The number of users is a direct reflection of the station criticality with respect to size, number of lines connected, and, consequently, number of levels in a station. The adjacent businesses represents the importance of the station derived from its respective location in proximity to high residence areas, recreational areas, and other areas of high passenger frequency like hospitals, universities, and, schools. The failure in this case means direct loss to passengers and businesses depending on this station as a main transportation mode. The interruption rate refers to the frequency of interruptions occurring at that station per year and reflects the station reputation and reliability with respect to the passengers and their dependability on the station for their daily trips. The degree of interruption refers to whether this interruption will cause total station closure, partial closure, or can be repaired without station closure and service disruption. The station closure depends mainly upon the location of the failing component in the network hierarchy. Referring to the systems analysis approach; if a component operates in a series system, then its failure will cause closure to the station (either partial or total) based on the component criticality. Whereas in a parallel system, failure of a component does not require closure of the station since the system can still function effectively. It is stressed that in our analysis, the failure of any component is not considered critical enough to cause serious injury or death. In such case, the station will be fully closed since the human life is the most valuable and cannot be compared with any consequences.

Impacts of failure show different levels of importance with respect to their share in measuring CoF. This requires adding a weight component to the CoF equation to account for the different weights each impact imposes. On the other hand, the defined impacts of failure along different categories are interdependent, hence, loops of cause and effect flow between them. The effect of a single impact cannot be measured independently without considering how other impacts affect and are affected by its occurrence. The FANP was therefore selected to obtain the relative weights of these factors. The FANP addresses the interdependency inherent in the relation between these factors and accounts for the uncertainty caused by the use of expert opinions due to the topic subjectivity. In order to estimate the overall consequence of failure for each station the following steps are adopted:

- Identify CoF attributes of different elements using literature review and expert opinion,
- Categorize CoF according to their social, operational, and financial Impacts,
- Estimate the consequences of failure weights(CW_i), using expert opinion and FANP,
- Compute the severity scores (Ss_i) using expert opinion, station configuration and historical data,
- Compute each element consequence of failure index (CF_i) using equation 1,

[1] $$CF_i = CW_i * Ss_i$$

- Aggregate the CoF indices for different elements per station using equation 2 and what-if scenarios,

[2] $$CF|station = \sum_{i=1}^{n} CF_i$$

Where: i= elements operating per station

- Use the $(CF|station)$ to prioritize subway stations for rehabilitation according to the CoF index.

4. Illustrative Example

An illustrative example is presented to demonstrate the potential benefits of the above-mentioned methodology. In this example, CoF are compared across three stations for a typical station system slab. The slab is located in the first floor of the station. Three arbitrary stations are selected for comparison and given the notations A, B, and, C respectively. Hypothetical attributes weights and scores are assumed for comparison purposes.

4.1 Criteria and Sub-criteria Weight (CW_i) Determination

i. Construct the model as a network of clusters and nodes, with the clusters acting as the main criteria and the nodes as the sub criteria. Our case is formulated as a network with single control criteria that is the consequences of failure. The objective is to determine the relative weight for the different impacts of failure through considering the relations between main criteria and sub criteria and introduce them as clusters, nodes, and influence links in the network created using the Super Decisions® Software developed by Saaty (2012) shown in Figure 2.

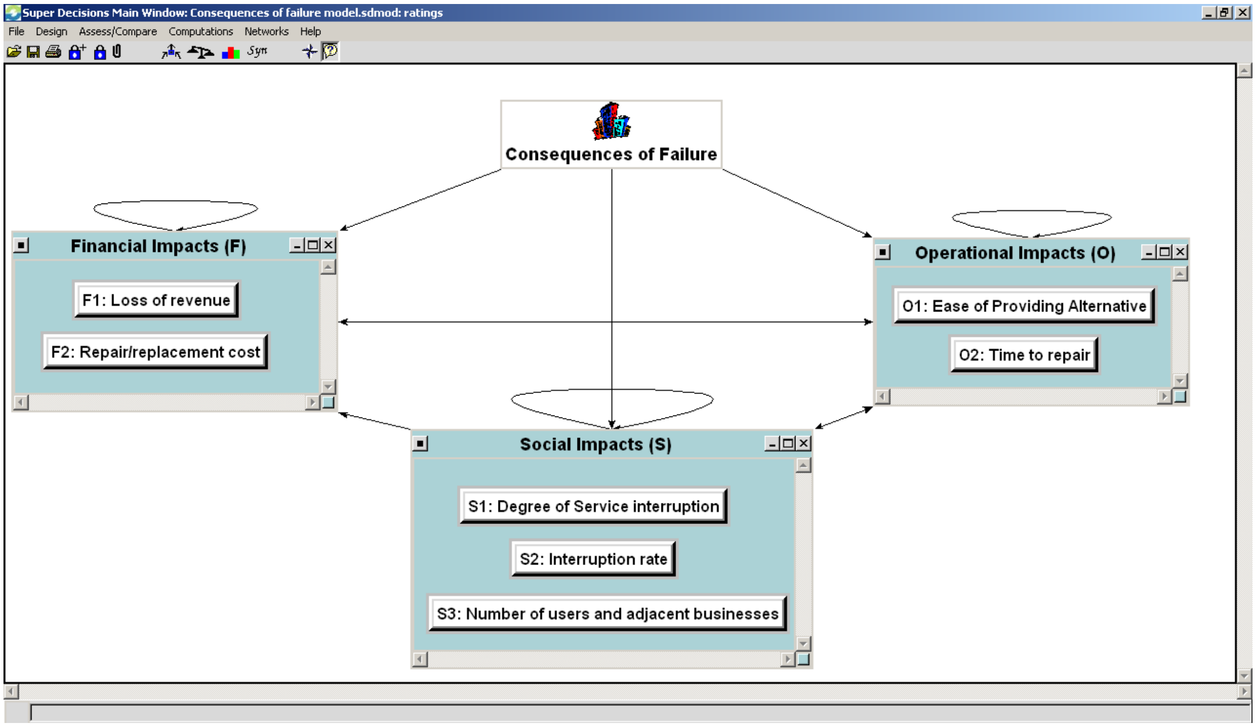

Figure 2: Consequence of Failure ANP Network

ii. Conduct Pair wise Comparisons using a fuzzy extension of the 9-point fundamental scale proposed by Saaty (2001) and shown in Table 1. Triangular fuzzy numbers are selected for their wide applicability and ease of comprehend by decision makers. The fuzzy scale is used to represent subjective pairwise comparison of the defined nods and clusters to capture the vagueness of the comparison. The pairwise comparison is conducted on three levels;
    - Between main criteria (social, financial, and operational impacts) regarding goal (CoF),
    - Between main-criteria with respect to each other (outer independence), and,
    - Between sub-criteria with respect to main-criteria (inner independence)

Table 1: Saaty Linguistic scale of relative importance

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

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 3. It is required to derive crisp priority vector $w = (w_1, w_2 \ldots w_n)^T$, such that the priority ratios w_i/w_j are approximately within the scopes of the initial fuzzy linguistic judgments provided,

[3] Max λ

Subject to $(m_{ij} - L_{ij})\,\lambda w_j - W_i + L_{ij} W_j \leq 0$

$(u_{ij} - m_{ij})\,\lambda w_j + W_i - u_{ij} W_j \leq 0$

i= 1, 2, 3, … , n-1, j= 2, 3, … , n, 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).The nodes, grouped by the clusters they belong to, are the labels of rows and columns of the supermatrix.

v. Develop the weighted super matrix from the unweighted supermatrix. The weighted supermatrix is obtained by dividing each entry in each row in the unweighted supermatrix by the total summation of its relative intersecting column.

vi. Develop the limit supermatrix by raising the weighted supermatrix to sufficient large powers until convergence occurs**.**

Steps (iv) to (vi) are done using the Super Decisions® Software developed by Saaty (2012).

vii. Calculate Global weights from the limit supermatrix by proportioning elements of each cluster to themselves.

The expected outputs from the previous steps are local and global weights of criteria and sub criteria as shown in Table 2.

4.2 Severity Score (Ss_i) Calculations

The attributes considered are diverse and have different performance scales. Therefore, the maximum and minimum values for the scales are identified to allow the score normalization. The attributes and their upper and lower limits are defined in Table 3. The station score is obtained for the three stations under comparison with respect to the failed slab. Based upon the element and the repair methodology, if the element is in a series system, then its failure will imply the total closure of the station for repair purposes, that means full service interruption for this line of the station and consequently full loss of revenue (100%). In case of an element in parallel, the expert is asked to provide a percentage for the expected service interruption due to the repair/replacement activities. This percentage is expected to be the same for the loss of revenue; hence, even if only partial service interruption is expected, a loss of revenue can still be expected due to station congestion, service delay due to repair/replacement activities, customers shifting of transportation mode due to the delay, etc. The same percentage also applies for the number of users and adjacent businesses affected by the service interruption/loss.

Table 2: Example of local and global criteria obtained using ANP calculations

Main Criteria	Global weight	Sub Criteria	Local Weight	Global weight
Financial Impacts	35.6%	Loss of Revenue	24.7%	8.79%
		Repair/replacement cost	75.3%	26.81%
Social Impacts	38.2%	Degree of service interruption	15.5%	5.92%
		Interruption rate	20.6%	7.87%
		No. of users and businesses	63.9%	24.41%
Operational Impacts	26.2%	Time to repair	73.7%	19.31%
		Ease of Providing Alt.	26.3%	6.89%

Table 3: Consequence of failure definition and scales

Impact of failure	Attribute	Definition	Score	
			Maximum	Minimum
Financial	Repair and replacement cost	Direct cost for replacement/repair of the failed component	Replacement cost/element	Repair cost/element
	Loss of revenue	Profit loss due to service interruption, stoppage, reputation loss, etc. provided by the decision maker as the expected % of service interruption	100%	0%
Operational	Ease of providing alternative	Measured by the decision maker on a 1-10 scale as the ease and speed of providing an alternative	Difficult and timely to provide = 10	Easy, fast and efficient =1
	Time to repair	Required time to return the failed component to a full functioning state	365 days	0 days
Social	No. of users and adjacent businesses	The number of users and businesses as a percentage affected by the service interruption	100%	0%
	Interruption Rate	Defined by the decision maker as the maximum allowable number of interruptions per year	6	0
	Degree of service interruption	Estimated as a % based on element configuration and decision maker	Full interruption = 100%	No interruption = 0%

Station B is assumed as an interconnecting station located in a vital location in proximity to critical businesses. Because of its importance, it is regularly maintained and several bus lines pass by the station. Therefore, sub criteria O1 is given a low score since a network of buses already exists and S2 has a low value. On the contrary, stations A and C are single line stations and the bus lines passing by them are limited, thus, more time, and resources are required to provide an alternative service. The failure in station A is severe and slab replacement is required, which implies a higher degree of time to repair (O2), service interruption (S1) and, consequently revenue loss (F1). Besides, the repair cost (F2) is the maximum expected. The deterioration in stations B and C is less, therefore only partial repair is required, and consequently less scores for attributes F1, F2, S1, and, O2. Based on the previous description, the scores for the different attributes are assumed as shown in Table 4.

Table 4: Stations Scores for failure attributes

Main Criteria	Sub Criteria	Stations Normalized score		
		Station A	Station B	Station C
Financial Impacts	F1: Loss of Revenue	5	3	2
	F2: Repair/replacement cost	10	5	3
Social Impacts	S1: Degree of service interruption	5	3	2
	S2: Interruption rate	3	1	3
	S3: No. of users and businesses	6	8.5	4
Operational Impacts	O1: Ease of Providing Alt.	6	1	5
	O2: Time to repair	5	2	1

4.3 Consequence of failure index (CF) calculations

Using criteria weights and severity scores shown in Table 2 and Table 4 respectively, the consequence of failure index is calculated for the slab along the three stations and presented in Table *5.*

Table 5: Final Consequence of Failure indices

Sub Criteria	Global weight	Stations Consequence of failure index		
		Station A	Station B	Station C
Loss of Revenue	8.79%	0.4395	0.2637	0.1758
Repair/replacement cost	26.81%	2.681	1.3405	0.8043
Degree of service interruption	5.92%	0.296	0.1776	0.1184
Interruption rate	7.87%	0.2361	0.0787	0.2361
No. of users and businesses	24.41%	1.4646	2.07485	0.9764
Ease of Providing Alt.	6.89%	0.4134	0.0689	0.3445
Time to repair	19.31%	0.9655	0.3862	0.1931
Compiled scores	100%	6.4961	4.39045	2.8486

From the previous results, station A was found to have the highest compiled CoF index and thus, the highest repair priority with respect to stations B and C in case of station system slab failure. This example proves the proposed technique's capability to rank repair priorities, when comparing between three stations in term of a single failed element while considering multi-perspective failure consequences. A wider level analysis involves comparison between stations in terms of all existent elements and using what-if scenarios, different cases of elements failure can be studied. In terms of CoF estimation, this research is pioneer in covering the topic through identifying tangible and intangible expected CoF and measuring their respective weights and scores. The analysis methodology demonstrates using FANP with application of the FPP method that adds a level of criteria interdependence to the analysis and ensures a comprehensive analysis despite the high topic subjectivity.

5. Conclusion

The current paper presents multi-perspective consequences of failure estimation model for subway metro stations. The presented model adopts a qualitative approach for impacts of failure estimation with the help of expert opinion and available historical data. This permits measuring diverse and intangible CoF that are usually difficult to estimate and capture. The research revealed clusters of CoF that are interdependent and strongly connected, hence, the FANP is used as the main analysis methodology to account for the cause and effects loops flowing in between consequences of failure. The FANP combines the advantages of the ANP of modeling the system's complexity and goes beyond that to account for the imprecision and uncertainty associated with mapping of an expert's judgment to a crisp number through integrating the fuzzy concept into the analysis process. The developed model offers a framework for clustering subway station according to the CoF severity on element and station level. An illustrative example is presented to validate the model and illustrate how repair priorities are identified when comparing an element failure across a number of stations. The methodology is believed to help decision makers prioritize rehabilitation needs across different stations in a network based upon the multi-perspective failure impacts measured. For future research, the proposed methodology will be applied in real case studies for reliability and validation matters.

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