An Integrated Risk-Based Asset Management Framework for Subway Systems

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A Thesis

In the Department

Of

Building, Civil & Environmental Engineering

Presented in Partial Fulfillment of the Requirements

For the Degree of

Doctor of Philosophy (Building Engineering) at

Concordia University

Montreal, Quebec, Canada

December, 2014

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ABSTRACT

An Integrated Risk-Based Asset Management Framework for Subway Systems

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Subway systems play a vital role connecting thousands of people to different destinations on a daily basis. The Canadian infrastructure report card recommended encouraging infrastructure owners to establish asset-management plans based on rates of deterioration and community service levels. Moreover, the 2013 report card for America's infrastructure assigned a grade D to transit systems indicating they are in a poor condition with strong risk of failure. A possible solution proposed by the 2013 report card is adopting a comprehensive asset management system to maximize investments in light of the fund scarcity dilemma.

The main objective of this research is to develop a risk-based asset management framework for subway networks. The framework works along three interrelated sub-models followed by two main models. A generic subway hierarchy is proposed and risk is assessed using three sub-models; probability of failure, consequences of failure and criticality index. Probability of failure is predicted for different structural elements using inspection reports and Weibull reliability function. Consequences of failure are assessed based on seven criteria along financial, social, and, operational perspectives. A criticality index is introduced to the classical risk equation to assess the functional importance of a station in its location using seven attributes along three main criteria. The Fuzzy Analytical Network Process is employed to analyze experts' feedback used in the consequences of failure and criticality sub-models. This insures incorporating interdependency between criteria and fuzziness of the analysis. The three sub-

models are used as inputs in a fuzzy inference engine to compute the predicted risk index. A set of thirty rules derived from experts through interviews and questionnaires is used to shape the relation between the fuzzy output and input variables. Finally, the second model is developed for a risk-based budget allocation model. The model utilizes the risk index components as objective functions. Decision variables are identified as five generic rehabilitation actions along their cost, time, and percentage improvement. The model provides the recommended rehabilitation action in light of the network total risk index and the available budget per time span.

This is the first risk assessment framework proposed in the subway networks domain. Using a network analysis approach, the elements of a risk index are analyzed and aggregated from elements to lines and segments levels. The model revealed probability of failure to be the main driver of a risk index followed by criticality index and last, consequences of failure. Within the expected consequences of failure, social impacts had the highest impact (38%) based on experts' feedback. The criticality index sub-model revealed station location to be the most important criteria (35%) followed by station nature of use (33%) and finally, station characteristics (32%). A segment of six stations from Montreal subway network is analyzed. The assessment indicates two stations with high risk indices showing the necessity of an intervention action. The budget allocation model prioritizes stations for rehabilitation according to the decision maker's risk appetite, assumed at 0.6. The revised risk index for STA 4 dropped from 0.821 to 0.521 and the overall segment index dropped to zero.

This research presents a basis for evaluating subway infrastructure on a structural and functional basis. It assists authorities to derive an informed rehabilitation decision using a generic and consistent framework. The heuristic decision making process followed by authorities is translated into a detailed framework that can be easily implemented and updated. The presented outline can be equally used for segments or the entire network.

ACKNOWLEDGEMENT

The guidance and blessings of Allah showered me through each stage of this work. I am thankful for Allah for providing me with the power and strength to fulfill this research. May this work be beneficial for other to come and be counted in my good deeds.

Special appreciations to my supervisor, Professor Tarek Zayed, for his continuous support and valuable feedback. Working with Dr Zayed allowed me to develop as a researcher and student. His precious advice throughout this journey will always affect me as a researcher.

Thanks are due to my dear parents for their encouragement and up bringing that made me reach this point in my life. The continuous support and inspiration of my beloved sister, Iman and Heba, walked me though a lot of hardships at several stages.

I dedicate this thesis to my dear husband, Mohamed Gomaa and my two blessings Sara and Yusuf. He sets an example with his constant support, love, understanding and motivation all through the way. His infinite encouragement always strengthened me. Sara and Yusuf bared with me through all my long working hours and tough schedule.

I would like to acknowledge the Société de Transport de Montréal (STM) and its personnel for their positive participation. Their valuable feedback and provided data strengthened the research.

I am grateful for all my friends who supported me and prayed for me all through the way. Thanks to all my colleagues at the Construction Automation Lab who provided feedback and support.

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CHAPTER 1. INTRODUCTION

1.1 GENERAL

Subway systems are essential public transit assets and one of the safest modes of transportation. They deliver thousands of passengers daily to different destinations overall the city. Subways represent a class of safety-critical assets, which should be studied in depth since their failure has serious consequences like multiple fatalities or injuries, partial, or complete loss of service, major traffic disruptions, and other socio-economic effects. A subway network is typically composed of diverse components and systems, which operate simultaneously to deliver the required service. This diversity of components causes a level of complexity, making the network difficult to assess and maintain. Preserving a subway network at the desired level of service is a tough task given the scarcity of fund that is a common problem for public authorities.

The Transportation Society of Montreal 'Société de Transport de Montreal' (STM) has estimated the improvement value of its network to be 493 million CAD in 2007. It also estimated a required amount of 5.1 Billion CAD for the maintenance of the subway system infrastructure for the next ten years (Semaan 2011). However, STM is faced by the problem common to all public authorities that is lack of fund, which prevents it from addressing all rehabilitation needs of the different subway components in a timely manner. In addition to the failure probability exhibit by the different components in a network, these components are characterized by multiple failure modes and different consequence of failure besides varied levels of criticality. This makes the prioritization procedure of components and stations for rehabilitation a difficult and complex task. This calls for adopting a risk assessment procedure to prioritize the needs of various systems in a subway network while addressing the different levels of consequence of failure and criticality. The risk of failure assessment of subway network conveys critical information on the probability of failure of the structure and more importantly on the consequence of failure. For instance, the risk associated with the failure of a wall in a station is very different from that of a wall in a tunnel. It is also very different from the loss of serviceability and functionality of a slab. Such information cannot be captured by the conventional condition ratings, which is the practice adopted by most transit authorities. It is therefore clear that a risk assessment model is critical for a subway network analysis. Moreover, the information retrieved from such a model will form an asset for elements prioritization and budget allocation.

This research presents a comprehensive risk-based budget allocation framework. The proposed methodology assesses the failure risk of a subway network through analyzing the probability of failure, consequence of failure and criticality of the different components composing the network. The fuzzy inference engine is used to incorporate the risk components fuzziness into a risk index model. Subsequently, the output from the risk model is used in a risk-based budget allocation model for efficient optimization. The proposed framework sheds the light on intangible aspects of functionality in a subway network that are often neglected. It incorporates a wide spectrum of perspectives for a robust subway assessment.

1.2 PROBLEM STATEMENT

The Canadian Urban Transit Association (CUTA) estimated that 140 Billion CAD is required for maintaining, rehabilitating, and replacing the subway infrastructure between 2012 and 2016 (CUTA 2012). According to Semaan and Zayed (2009), the problem faced by STM and most transit authorities is the lack of proper rehabilitation plans for subway stations. A proper rehabilitation plan should include setting priorities for rehabilitation, budget allocation, investment planning, and financing. Such an exhaustive plan requires assessment tools for the conditions of stations as well as the expected consequence of failure. Abu-Mallouh (1999) evaluated a number of subway systems and concluded that most stations evaluated were more than 95 years old and in need of rehabilitation proportionate to their ages. In an effort to assess the stations conditions, Semaan (2006) developed the Subway Station Diagnosis Index Model to diagnose specific subway stations and assess their conditions using an index (0-10).

Correspondingly, Farran (2006) developed the Maintenance and Rehabilitation Planning for Public Infrastructure (M&RPPI) model which addressed Life Cycle Costing (LCC) for a single infrastructure element with probabilistic and condition rating approach for condition state. Whereas (Semaan 2011) developed the SUbway PERformance (SUPER) model, which evaluates the structural performance of different components in a subway network and develops performance curves of subway components and the entire network. Apart from these efforts, the literature demonstrates a serious lack of models that assess the performance of subway networks in terms of measuring their probability and computing the expected consequence of failure. Most of the efforts documented developed condition assessment indices and ranked stations accordingly. This method of ranking is not accurate since it adopts a structural view of the network while neglecting the consequence of failure and consequently the priority of stations for rehabilitation.

The decision taken by the management to favor an option over the other should consider the consequences of each option. Risk analysis supports managers and experts to make a good decision by highlighting the consequences and threat embedded in different decisions (Gargari 2009). In this essence, risk-based asset management is an integrated tool to identify, analyze, and finally prioritize rehabilitation of high-risk assets. The subway system being a high risk asset that transports millions of passengers on a daily basis and affects the life of a vital city like Montréal. An imperative need exists to develop a comprehensive risk assessment model that combines the probability and consequence of failure together with station criticality in a single index to be used to prioritize subway network systems for rehabilitation. As transit systems grow, good asset management practices will be essential to effectively manage complex systems and growing ridership (America's report card 2013).

1.3 RESEARCH OBJECTIVES

The main research objective is to develop a comprehensive risk-based budget allocation framework, to assesses network level risk and prioritize rehabilitation of network components accordingly. To achieve the main objective, a number of sub objectives are identified as follows:

- Identify and study the hierarchy of a subway network to highlight its building blocks and the focus of analysis.
- Develop models for probability of failure, consequence of failure, and criticality index of various subway stations/components.
- Integrate the three models into a global risk assessment model.

1.4 RESEARCH METHODOLOGY

The three sub-models composing the risk index model are Probability of Failure sub-model, Consequence of Failure sub-model, and Criticality Index sub-model. The output from these sub-models yield the basic inputs required for the risk equation; these are;

- The probability of failure (PoF_i); provides the expected failure probability based on the level of deterioration of each element,

- The consequence of failure (CoF_i); provides the expected consequence of failure in terms of financial, operational, and social impacts of failure.
- The criticality index (C_R); the criticality index is introduced to measure the individual criticality of each station based upon subjective attributes that change between stations.

The output from the three models will be normalized and integrated into a single global risk equation; the fuzzy inference engine will be used to combine the three sub-models to the final model. The expected output is a fuzzy risk surface visualizing the different combinations for the probability of failure, consequence of failure and criticality values. Using historical data, various maintenance options for different components together with their expected cost and increase in level of service can be obtained. This information is further combined with the risk index in a budget allocation model. The output of the last model is the optimized choice of maintenance action and component to be rehabilitated by minimizing the overall risk index.

1.5 THESIS ORGANIZATION

Chapter 2 presents a literature review on the existing methods adopted by authorities and researched by academics to manage the existing subway networks. The different approaches are discussed and investigated. Limitations and gaps in each approach are presented. Analysis methodologies selected to develop the model are also discussed with justifying their choice of use. Chapter 3 provides an overview of the proposed methodology to be used in this research. It starts by developing the three sub-models composing the risk model. This is followed by the risk-based budget allocation model. Chapter 4 presents the data collection stage which is an integral part of the research and model development. Chapter 5 presents a model adopted from the literature to validate and implement the proposed methodology and prove its robustness.

Finally, chapter 6 summarizes the research and presents the contributions and future work suggestions.

CHAPTER 2. LITERATURE REVIEW

2.1 GENERAL

Montreal metro is one of the safest and oldest networks in North America. For more than 35 years, it has been an integral part of Montreal's life covering a total operational length of 60.5 km. Nevertheless, stations are constantly subject to different types of threats ranging from threats caused by natural deterioration of the stations to threats due to vulnerability and the open nature of the metro system. A standard procedure for dealing with these different threats and considering them to rank stations according to their risk level is not yet developed. Although transit authorities have typical inspection reports, models for interpreting these reports to assess risk of different components of subway networks does not exist.

2.2 SUBWAY ASSESSMENT EFFORTS

Public authorities worldwide developed multiple practices to manage their subway system in a functioning state in light of the fund scarcity. The literature also demonstrates research efforts to assess the condition of metro stations and develop a method for ranking stations for maintenance and rehabilitation. Each transit authority developed different preliminary rating methods according to their own management plans and rehabilitation needs. Table 2.1 summarizes practices used by different authorities and outlines their basic features and limitations. The following section investigates the different methodologies developed by scholars and applied by authorities.

Table 2.1 Summary of Practices Applied by Subway Authorities

Subway Authority	Program implemented	Limitations
Société de Transport de Montréal	• Applied two consecutive programs: "Réno-Stations I" and "Réno-Station II" to prioritize stations' rehabilitation. • The Structural deterioration identification was based upon expert visual inspection. • The inspector assigned each condition a score based on a predefined scale and measured the physical condition (CEM) and the performance condition (CEP).	i. Considered stations separately without considering the whole network, ii. Ranked stations without actual evaluation of the condition or deterioration of the stations iii. Rehabilitation based on a simple selection procedure of the station age and expert opinion only.
California Train Transit System	• Developed a five-level evaluation system of stations and ranked them from excellent to poor. • The rank was done based on 10 criteria and the scores were combined using the weighted average approach.	i. Did not consider the subway as a network ii. It ranked stations without actual evaluation of the physical and structural condition of the station.
Metropolitan Transit Authority of New York Transit	• Developed a ranking system for condition assessment • Different factors were considered and each station was ranked according to its priority, by allocating points to the different factors	i. Ranked stations without actual evaluation of the station deterioration level ii. Did not predict the future rating, iii. A station level and not a network level model.
London Transport	• Developed the Key Performance Indicator (KPI) • The KPI evaluated the performance of the station from its customers' point of view through direct surveys and interviews. • A (0-10) evaluation scale based upon 23 items	i. Did not measure the subway elements failure over time ii. Considered stations separately without considering the whole network, iii. Ranked stations without actual evaluation of the condition or deterioration of the station
Paris Rapid Transit Authority	• Developed a selection procedure for stations in need of rehabilitation • The study assigned to LAMSADE, University of Paris-Dauphine in France used a seven criteria selection procedure.	i. Stations ranked using seven nonfunctional criteria without actual evaluation of the condition or deterioration of the station.

2.2.1 The Subway Station Diagnosis Index (SSDI) Model

One of the first models addressing the topic is the Subway Station Diagnostic Index (SSDI) Model developed by Semaan (2009). The SSDI is a condition assessment model that diagnoses specific subway stations to assess their conditions using an index (0-10). The SSDI describes a station's condition state, its deterioration level as a percentage, and, the proposed subsequent actions. The SSDI model considers the effect of functional and operational criteria, which are directly linked to maintenance and repair of subway stations based on condition assessment (Semaan 2009). The model defines four criteria namely: (a) structural/architectural, (b) mechanical, (c) Electrical, and (d) electrical communication/security. The model then utilizes the Analytic Hierarchy Process (AHP) to evaluate their weights and the Preference Ranking Organization METHod of Enrichment Evaluation (PROMETHEE) and the Multi- Attribute Utility Theory (MAUT) to determine the Station Diagnosis Index (SDI) on a global station level (Farran and Zayed 2009). The SSDI model had several limitations; first, it did not study the structural deterioration of the station over time; it is a rather diagnostic model. Second, the model studied stations only and did not consider other structures despite their vitality, and, last, it cannot be applied on a network-wide scale (Semaan 2011).

The SSDI model is deterministic, thus, it failed to capture the uncertainties inherit in the problem parameters and the collected data. The stochastic Global Station Diagnosis Model (GSDM) developed by (Semaan and Zayed 2010) resolved this problem. The GSDM model identified different functional condition criteria in a subway station and determined the criteria weights using the AHP. The model used PROMETHEE to find out the multi-criteria performance index and Monte Carlo simulation to calculate a global diagnosis index.

2.2.2 Maintenance and Rehabilitation Planning for Public Infrastructure Model

In a corresponding effort, Farran (2006) developed the Maintenance and Rehabilitation Planning for Public Infrastructure (M&RPPI) model. The M&RPPI addressed life cycle costing for a single infrastructure element with probabilistic and condition rating approach for condition state. The model used Markov Chain (MC) theory to evaluate the deterioration of structural element. Different repair actions and consequent costs are considered by the model using Genetic Algorithms to optimize the Life cycle cost of the structural element. The M&RPPI model required extensive data to operate; moreover, it is used to assess only one element of the structure and consequently cannot be used on a network level analysis.

2.2.3 The SUbway PERformance Model

(Semaan 2011) developed the SUbway PERformance (SUPER) model to evaluate structural performance of different components in a subway network. The developed model performs physical, functional, and, integrated performance assessment at the component level and constructs performance curves at the component, line, and network levels. The SUPER model uses AHP and MAUT to assess the integrated components' performance. It also utilizes a reliability-based cumulative Weibull function to construct performance curves of components. In addition, parallel/series network modeling technique was adopted to evaluate and construct performance models of the systems, lines and network.

The model measures the elements performance as the integrated effect of the Functional Performance (P_F) index and the Physical Performance (P_P) index. The main steps of the SUPER model are outlined below;

(i) *Using the inspection reports*,

1. The different cracks and defects scores for each component are evaluated.
2. The Analytic Hierarchy Process (AHP) is used to evaluate different cracks and defects weights.
3. The Multi-Attribute Utility Theory (MAUT) is used to calculate the physical performance (P_P) index and the functional performance (P_F) index.
4. Finally, the integrated performance index (*PI*) is evaluated by combining these two indices using the Multi-Attribute Utility Theory (MAUT).

(ii) *Using the reliability-based Weibull cumulative function*, the ideal performance model is constructed for each element. This ideal model is updated using the integrated performance indices evaluated in the previous step. The predicted performance model is then developed which refers to the final updated performance model.

(iii) *Using parallel-series network modeling techniques,*

1. Reliability curves are developed for the different stations, tunnels and auxiliary structures of the subway network.

2. Reliability curves of the different lines of the subway network are developed.

3. Reliability curves for the complete subway network are developed.

The structural performance of a component is reflected by two indices; the physical performance index (P_P), and the functional performance index (P_F). While the physical performance index reflects the physical fitness of the component through deterioration due to regular aging, excessive or abusive use, and bad maintenance. The functional performance index reflects the component's suitability to function as designed.

These two indices are independent and thus measured separately. The component's performance is measured by means of these two indices. The reader is referred to (Semaan, 2011) for more details regarding the factors used to measure these indices. The physical and functional performance factors cannot be measured, however, they cause deficiencies such as cracks and defects which can be measured and quantified. The cracks and defects are measured visually as per Ministère des Transports du Québec (MTQ) regulations.

The Functional Performance index (P_F) is defined in Equation (2.1)

$$P_F = \left(\prod_{DbC=1}^{5} \overline{S\mathrm{DbC}}^{wDbC}\right)^{WDb} * \left(\prod_{CbC=1}^{4} \overline{S\mathrm{CbC}}^{wCbC}\right)^{WCb} \qquad (2.1)$$

Where,

$\overline{S_{DbC}}$= Design-based cracks normalized score, w_{DbC} = Design-based cracks weights, w_{Db}=Design-based category weight, $\overline{S_{CbC}}$= Construction-based cracks normalized score, w_{CbC} = Construction-based cracks weights; and, w_{Cb} = Construction-based category weight.

Similarly, the Physical Performance Index (P_P) is defined in Equation (2.2):

$$P_P = \left(\prod_{\mathrm{CHbD}=1}^{8} \overline{\mathrm{SCHbD}}^{\mathrm{wCHbD}}\right)^{\mathrm{WCHb}} * \left(\prod_{\mathrm{MbD}=1}^{4} \overline{\mathrm{SMbD}}^{\mathrm{wMbD}}\right)^{\mathrm{WMb}} \qquad (2.2)$$

Where,

$\overline{S_{CHbD}}$= Chemical-based defects normalized score, w_{CHbD} = Chemical-based defects weights, w_{CHb} = Chemical-based category weight, $\overline{S_{MbD}}$= Mechanical-based defects normalized score, w_{MbD} = Mechanical-based defects weights; and, w_{Mb} = Mechanical-based category weight.

The Integrated Performance Index (P_I) is shown in Equation (2.3);

$$P_I = P_F^{Wpf} * P_P^{Wpp} \tag{2.3}$$

Where,

W_{pf} = weight of functional performance index, W_{pp}= weight of physical performance index, such that $W_{pf}+W_{pp} = 1$.

Using the reliability-based Weibull cumulative function, the ideal performance curve is constructed for each component. This ideal curve is updated using the integrated performance index evaluated in the previous step (P_I). The reliability function for the Weibull distribution is given by Equation (2.4)

$$R(t) = 1 – F(t) = e^{-(\frac{t-\alpha}{\tau})^{\delta}} \tag{2.4}$$

Where α = location parameter, τ = scale parameter, δ = shape/slope parameter, e = exponential function and t = time.

The Ideal Performance Curve (IPC) has the same shape of Equation (2.4) and is defined in Equation (2.5).

$$\mathbf{P_I^{IPC}(T) = \alpha .\, e^{-\left(\frac{t}{\tau}\right)^{\delta}}} \tag{2.5}$$

Where,

IPC = Ideal Performance Curve, t = time, e = exponential function, α = Initial condition factor or location parameter, τ= Service Life (SL) adjustment or scale parameter, and, δ = Deterioration parameter.

The following assumptions are considered when constructing the IPC (Semaan 2011).

- At initial time (t = 0), the slope of the curve equals zero
- The ideal Service Life (SL) is assumed 100 years for infrastructure concrete elements.
- The Useful Service Life (USL) is the life of the structure at the minimum acceptable performance, or the performance threshold.
- The performance threshold equals 2/5=0.4
- The minimum performance is equal to 1/5 = 0.2

The ideal performance curve represents the theoretical performance curve of the component, whereas, the real reduction of performance over time is best represented by the Updated Performance Curve (UPC). For each inspection, the PI is evaluated for all inspected components. The updated curve is fitted to pass through this specific PI point. From this point, new Weibull parameters are calculated. After each inspection, the UPC is constructed and the Updated Service Life ($USL_{Updated}$) is calculated. For the conditions followed for creating the UPC, the reader is referred to (Semaan 2011). The performance index for the updated performance curve can be calculated using equation (2.6)

$$P_I(t)^{UPC} = 1.\, e^{\ln(P_{Ii})\left(\frac{t}{t_i}\right)^3} \tag{2.6}$$

Where, t_i = inspection time, and P_{Ii} = integrated performance index at time t_i.

The Updated Performance Curve following the last inspection is considered the final Predicted Performance Curve (PPC). The PPC considers the entire inspection information about the history of the component including the last inspection. In case of components without inspection reports, the ideal performance curve applies to these components. For components, which have more than two inspection records, the predicted performance curve depends on the last inspection.

This is the only model available in literature that addresses the subway from a network level. Nevertheless, the model cannot be used to prioritize stations for rehabilitation and did not analyze consequence of failure or the relative station importance.

Apart from the listed efforts, the literature does not provide any models for conditions assessment of subway networks, nor does it document any efforts to compute the expected consequence of failure for subway stations. Most of the methods ranked stations based on arbitrary measures and did not consider consequence of failure which is not accurate since consequence of failure differ from one station to another and consequently the priority of stations for rehabilitation. The sections following demonstrate the current practices adopted by some transit authorities to maintain their subway networks.

2.2.4 Société de Transport de Montréal

The Montreal subway is one of the oldest systems in North America. The first lines were built in 1966, followed by extensions for the existing lines; new stations were built in 1976, 1987, 2001, and 2003. In 1990, the Société de Transport de Montréal (STM) launched the "Réno-Stations" program that targeted structural and architectural renovation of the oldest stations in the network. The first phase "Réno-Stations I" was implemented in 1990 followed in 2005 by "Réno-Station II" program to address the remaining older stations not included in the first phase of the program. The structural deterioration was identified in these two programs based upon expert visual inspection that measured two conditions: the "Condition d'État de Matériel" (CEM), and the "Condition d'État de Performance" (CEP). The CEM represents the physical conditions of the elements while the CEP represents their performance condition. These two programs however, did not consider the structural performance of stations as a whole; rather, it regarded them as separate elements. The worst of CEM or CEP was considered for the entire station, whereas the network performance as a whole was not considered. In addition, these two programs did not have a defined ranking scheme; stations were selected for rehabilitation based on their construction year and expert opinion.

2.2.5 California Train Transit System

The California Train (Cal Train), launched in 1864, is considered one of the oldest systems in the United States. In 1990, Cal Train began a station planning process to improve the performance of its stations. Cal train developed an evaluation system of stations and ranked them on a scale from (1) excellent to (5) poor based on 10 predefined criteria;

i. Ease of access to and from the station,
ii. Location of the station with respect to facilities,
iii. Parking spaces availability,
iv. Ease of using other transportation modes,
v. Cleanliness of stations and their appearance
vi. Physical and structural condition of the stations
vii. Public information, signs, telephones.
viii. Ticket selling machines
ix. Security
x. Safety

The criteria values were combined using a weighted average (Abu-Mallouh 1999). Nevertheless, Cal Train evaluation method did not develop deterioration models nor did it consider the subway as a network. In addition, it did not attempt to take consequence of failure or station criticality into consideration.

2.2.6 Metropolitan Transit Authority of New York Transit

With the operation and management of 468 stations showing various repair and rehabilitation needs, Metropolitan Transit Authority of New York Transit (MTA NYCT) developed a ranking system for stations selection for rehabilitation. Stations were ranked according to their priority to a set of selected factors by allocating points to each factor; the rating was only used to evaluate structural factors. Points were assigned for each factor and then added per station. The point's weight was considered the same for all stations (Abu-Mallouh 1999). The station condition depended on the total points as shown in Table 2.2.

Table 2.2 MTA NYCT Stations Condition Point Allocation

Scale	Condition Assignment	Maximum Points
5	Severe deterioration	51
4	Deteriorated condition	41
3	Moderate deterioration	31
2	Minor deterioration	20
1	No repair required	0

This ranking system had several limitations; the deterioration level was not specified, it did not predict existing or future rating. In addition, the point's weight was considered constant for all stations; this is not an accurate assumption since every station has unique characteristics in terms of its location, use, and, the expected consequence of failure.

In an effort to improve the MTA NYCT ranking system, Abu-Mallouh developed a Model for Station Rehabilitation Planning (MSRP) to optimize the number of stations accommodated within a given capital program for full and partial rehabilitation (Abu-Mallouh 1999). The model considered functional factors (structural, mechanical, communications, water condition, and safety) and social factors (daily usage, safety, and Level of Service) when selecting stations for rehabilitation. This model however had several limitations. It ranked stations without actual evaluation of the condition or deterioration of the station, performed budget allocation based on current station condition, considered stations separately without considering the whole network, considered a large number of factors which made it very lengthy to implement, and, used fictitious data that was not validated using real data (Semaan 2011). Moreover, the model did not consider consequence of failure or the separate criticality of each subway station.

2.2.7 London Transport

London Transit developed the Key Performance Indicator (KPI) in an aim to improve its system. The KPI evaluated the performance of stations from its customers' point of view using a direct evaluation of customer satisfaction through surveys and interviews. They asked customers to rate 23 items on a scale from 0 to 10, based on six criteria:

i. Cleanliness,
ii. Information services,
iii. Information on trains, i.e. station services (ticket gates, ease of access to platforms, buying a ticket and the degree of platform crowding.

iv. Safety and security,

v. Train services (crowding, journey time, smoothness of the ride...).

vi. Staff helpfulness and availability,

KPI is the overall weighted average of the 23-evaluation measures based on the user's satisfaction (Abu-Mallouh 1999). However, the KPI model is far from a deterioration model and does not measure the failure consequence of subway elements.

2.2.8 Paris Rapid Transit Authority

Paris Rapid Transit Authority (RAPT) worked on developing a selection procedure for stations in need of rehabilitation. The study used a seven nonfunctional criteria selection procedure (Roy et al. 1986). The criteria included; Platform users, Transit passengers, Coordination of works, Maintenance of wall and roof tiles, Visual aspect of the station, Level of discomfort, and, Environment (RAPT favored stations in rapidly changing and low-income areas). The result of this study was just a ranking model and not a deterioration model for the network. Moreover, the model did not measure the failure consequence or the individual criticality per station for the network.

2.3 ASSET AND NETWORK PERFORMANCE MODELS

Performance models can be classified into asset level models (infrastructure performance model) and network level models (network performance models) based on the nature of the data used in the model. An asset level model incorporates characteristics and factors related to the asset, which makes it best suited for infrastructures like bridges, sewers, water mains, and buildings. On the other hand, network-level performance models categorize network components having similar characteristics and models are developed for each group (Remenyte-Prescott and

Andrews 2011). In summary, asset level models enable model users to focus on an individual component of a network on a micro level; whereas, network level models are valuable when generating strategic assessments related to the overall condition of the whole system on a macro level. The objective of this research falls into the second category of developing a risk assessment model based on the probability of failure, consequence of failure, and criticality on the network level. Network-level performance models available in the literature were only developed for bridge and pipeline networks. No reported literature addressed the subway risk as a network despite its importance.

2.3.1 Asset Performance Models

An example of asset-level performance model is the M&RPPI model developed by Farran (2006). The model addressed Life Cycle Costing (LCC) for a specific infrastructure element with probabilistic and condition rating approach for condition state. The main scope of M&RPPI model is minimizing LCC. However, this model required a considerable amount of data and it worked on a component-level rather than a network-level problem. The Bridge Management System PONTIS ((Golabi et al. 1997), (Thompson et al. 1998)) is another example of an asset level performance model. PONTIS is a set of predictive and optimization models based on judgmental, engineering, and economic models and various databases. It used an interrelated Markovian optimization model for modeling bridges rehabilitation. Bridges have many different components degrading at different deterioration rates. For each component, PONTIS determined the best maintenance action at which the expected cost over an unrestrained time horizon is minimal (Frangopol et al. 2001).

2.3.2 Network Performance Models

Network-performance modeling techniques are categorized into system reliability approach and transportation network-optimization approach. The system reliability approach was first developed for equipment reliability and safety. Later, it was applied to infrastructures (Cox et al. 1998). A system should be regarded as a set of interdependent and interacting components that form a network fulfilling some safety objective. Lalonde, et al. (2003) used the system reliability approach in their effort to develop a decision support methodology for asset management applied to pipelines. Moreover, (Liu et al. 2005) developed a bridge-network reliability model using the same approach. They regarded bridges as links acting between nodes of interest, which could be cities hundreds of miles apart and could be shopping centers close to each other in a small local network. Whereas, nodes of interest were assumed in excellent condition, hence, links were considered the only possible failure component in the network.

The Transportation Network Optimization Approach originates from the Graph Theory, a mathematical division that evolved with Euler's formulation and solution for the Konigsberg bridge problem in 1736 (Liu 2006). The traditional transportation network problems regard network modeling and algorithms as pure minimum cost flow problems. These problems can be further specialized as transportation assignment, shortest path, and maximum flow problems in networks. Liu (2006) developed a bridge network-performance evaluation model combining both the systems approach and the transportation network (the shortest path) approach. Hastak et al. (2009) developed a web-based application tool called Analytical System for Planning of Infrastructure REhabilitation (ASPIRE) to help public agencies plan efficient rehabilitation strategies within limited budgets. The application estimated the physical conditions of facilities and allocated limited budgets based on the evaluated score. Derrible and Kennedy (2010) used an adapted Graph theory to assess subway systems on a network level. They assessed metro efficiency using three indicators relevant to ridership; coverage, directness, and connectivity. The model was applied to the plans of the City of Toronto and used to compare to 18 other systems in the world.

On the other hand, (Gonzalez et al. 2006) applied two adaptive control formulations under uncertainty, namely open loop and closed-loop, in an effort to develop maintenance and repair policies for railway infrastructures. The model assumed the facility deterioration as a Markov Decision Process (MDP), and that the planning agency characterizes the facility deterioration rates with Markovian models, each one determined by deterioration level and with a matrix of transition probabilities. The Reliability Centered Management (RCM) framework introduced by Carretero el al. (2003) was used to compute the criticality of each section to be then combined with the computed probability to obtain a risk figure.

2.4 RISK-BASED ASSET MANAGEMENT

Risk based asset management models have been implemented in the literature in various fields to quantify and assess the overall risks associated with different systems (Opila et al. 2011). The literature on risk assessment in subway network is very scarce; however, different risk assessment models were developed for other systems such as sewer and pipelines systems as presented hereinafter.

An ideal asset management system should include condition assessment and/or deterioration models, repair selection method, and prioritization of component for repair methodology. Risk management is the decision making process where actions are taken in response to the outcome of risk assessment. The term “risk” has variety of definitions. It is often used interchangeably to describe the probability of an event occurring or the consequence and damages due to the occurrence of this event. However, the most widely used definition of risk is the one defined by (Lowrance 1967) which combines these two factors into one equation, where risk is defined as the measure of probability and severity of adverse effects. It should be noted that elements with similar probability of failure show wide variation in terms of consequence of failure and vice versa. Critical elements with high consequence of failure usually compose a smaller portion of the overall network. Accordingly, focusing only on these elements would result in unbalanced management practices since unexpected failures may occur in less-critical elements, which constitute the majority of the network. On the other hand, focusing only on elements with high probability of failure results in a biased management strategy since the failure of an element of high consequence of failure may overcome any gains obtained from the proactive management of the less critical elements of the network.

A failure risk model for buried pipes was developed by (Kleiner et al. 2004); it represented consequence of failure on a fuzzy qualitative nine-grade scale from extremely low to extremely severe. Further, it combined consequence of failure with possibility of failure in order to determine the risk of failure by using a fuzzy-rule based system. Hahn el al. (2002) used six mechanisms to predict probability of failure for sewers. They used structural defects, interior corrosion, exterior corrosion, erosion, infiltration, and, operational defects. However, they utilized only two mechanisms to predict consequence of failure. Baris (2010) developed a risk assessment model at an individual pipe level by combining Probability of failure values determined by statistical deterioration modeling of sewer pipes and consequence of failure values determined by examining geographical, physical, and functional attributes of sewer pipes in the light of expert opinions. Fares (2008) developed a risk model for water main failure that evaluates the risk associated with each pipeline in the network. The model considered four main factors: environmental, physical, operational, and post-failure factors (consequence of failure) and sixteen sub-factors that represent the main factors. He used the Hierarchical Fuzzy Expert System (HFES) to develop the risk of failure model. Seattle Public Utilities calculated the risk of failure in monetary terms. They calculated the consequence of failure through multiplying a base repair/replacement cost with modification factors based on the attributes of sewer pipes (Martin et al. 2007). The Edmonton office of Infrastructure developed a risk assessment process to assess the scale and likelihood of different infrastructure failures related to current funding shortfalls. They concluded that adopting a risk assessment methodology helps identify a concrete course of actions and provides decision-makers with a tool to determine the potential impacts of not investing in specific infrastructure projects. Risk assessment also provides a guide for budget and investment planning (City of Edmonton Office of Infrastructure 2003).

2.5 PROBABILITY OF FAILURE MODELS

Making rational decisions regarding deteriorating infrastructure requires addressing sources of uncertainty associated with the deterioration process with and without maintenance appropriately (Frangopol et al. 2006). Two approaches are available when estimating failure probability of an asset: objective and subjective. Objective estimations require comprehensive data on loading and structural capacity of an asset. Wherever this data is not available, a probability is often determined using a subjective approach. This implies estimating the probability based on personal belief, experience, and knowledge of the asset to develop a probability estimate. The subway networks being a data scarce area, the probability estimation will follow a subjective pattern. Subway networks usually have a record of inspections that are scheduled either regularly or on discrete intervals. Inspection reports contain data on the condition of numerous components of the network. This data if correctly interpreted can be used as a method for probability estimation.

The models available for estimating the probability of failure can be deterministic, stochastic, or artificial intelligence models. Deterministic models include straight-line extrapolation models, regression models, and curve fitting models whereas Markovian models, reliability models, and failure-rate function models are example of stochastic models. Artificial intelligence models include case-based reasoning and neural networks (Morcous et al. 2002). The model in search here is one that resembles the deterioration of concrete; in addition, the model should be flexible enough to model the deterioration of a system as well as components in the system and account for the data scarcity problem existing in the subway sector. Bearing these guidelines into account, the different types of deterioration models were analyzed with respect to the research needs and the following was concluded:

- Deterministic models do not consider probabilistic behavior for the deterioration; in addition, they assume the deterioration rate as independent of time (Tran 2007).
- Multi-linear regression models are mathematically difficult to assess and are time consuming and data hungry which means they cannot be used to analyze subway networks (Semaan 2011).
- The Markov Chain models works on a basic assumption that transition probabilities are fixed, in addition to discrete transition time intervals, a constant population, and stationary transition probabilities (Collins 1972). It assumes for simplicity that transition states are independent (Madanat et al. 1997). Markov Chain modeling has the Markovian property, or lack-of-memory property, which means the probability of any future state,

given any past and present state, is independent of the past state and only depends upon the present state (Farran 2006). Moreover, it does not consider the interaction among different component and is not capable of considering the network deterioration (Van Noortwijk and Frangopol 2004a).

- Failure rate functions are useful in mechanical and electrical engineering fields, where equipment assume two states: a functioning state and a failing state. However, a degrading structure can be in a range of states. Thus, a serious limitation of failure rate models is their inability to be measured for structural components (Van Noortwijk and Frangopol 2004b).
- Reliability models are the only models flexible enough to analyze one component as well as a system of components. Its basic limitation is the amount of input data needed to perform a valid analysis.

Semaan (2011) developed the SUbway PERformance (SUPER) model which takes into account the scarcity of inspection reports. The SUPER model utilizes Weibull reliability curves to assess the performance of structural components by integrating condition and functional performance indices into one index. The model then develops a performance model for components, systems, lines, and the entire subway network. This model is deemed perfectly suited for this research. The model develops reliability performance curves for components up to the entire network, which makes it suitable for network-wide analysis. In addition, it overcomes the major drawback of data scarcity existent in subway network domain.

2.6 CONSEQUENCES OF FAILURE

A generic risk management system should identify probability of failure and Consequence of Failure (CoF) to be combined later to produce a representative risk index. The importance of determining consequence of failure cannot be over emphasized since a formal review of the consequence of failure diverts attention away from maintenance tasks having little or no effects and focuses on maintenance tasks that are more effective. This ensures that maintenance spending is optimized and guarantees the inherent reliability of the equipment is enhanced (Gonzalez et al. 2006). Consequence 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 consequence are mostly intangible such as service disruption, reliability loss, and, different social impacts. Therefore, researchers adopted diverse techniques for capturing the CoF expected for different infrastructures. The Triple Bottom Line (TBL) approach of sustainability offers a structured methodology to assess consequence of failure on three dimensions; financial, social and environmental. The main challenge in a TBL is measuring the different attributes. The area of sewer and pipelines had the largest share of literature dedicated to estimating consequence of failure.

The United Kingdom's Water Research Center (WRC 1986) prepared one of the most influential efforts for understanding and categorizing CoF for pipelines. CoF were assessed by considering socioeconomic impacts and 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 CoF values by examining 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. CoF measured the repair cost, traffic and business disruption, loss of production, and, type of service area. Seattle Public Utilities calculated risk of failure in monetary terms through estimating CoF as the multiplication of base repair/replacement cost with modification factors based on the attributes of sewer pipes (Martin et al. 2007).

2.7 CRITICALITY INDEX

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 importance of the system from a functional point of view. They computed criticality using 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, 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 in 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 reflected the importance of the components of a system in terms of functionality and importance in delivering the final service or product. However, by consulting the literature on subway stations, no effort was documented to measure criticality of subway stations or any attempts to classify stations other than on a structural basis.

2.8 THE ANALYTIC NETWORK PROCESS

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. MCDM can quantify uncertainties for comparison of decision alternatives. Such process is believed to help decision makers, technical experts, as well as stakeholders to systematically consider and apply value judgments to come up with the optimum strategic choice.

Saaty developed the Analytic Hierarchy Process (AHP) as a multi-criteria decision support methodology , AHP derives relative scales of absolute numbers known as 'priorities' from judgments expressed numerically on an absolute fundamental scale (Saaty 2005). The Analytic

Network Process (ANP) was developed as an extension to AHP problems with dependencies and feedback among criteria. ANP works on deriving relative priority scales of absolute numbers from a group of judgments. These judgments 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 MCDM problems. First, modeling the system's complexity using a network or for more specific cases, a hierarchy. Second, measuring on a ratio scale that ensures simplicity, and last, synthesizing to obtain the results. The local priorities in both methods are computed using pairwise comparisons; ANP however is superior to AHP by using the super matrix for the calculations to account for the interdependency between criteria and overcome the limitation of AHP's linear hierarchy structure (Saaty 2001). Table 2.3 illustrates the fundamental scale used for pairwise comparison as introduced by (Saaty 1980) and adopted later for ANP comparison as well. This scale demonstrates the numerical value used to convey the importance between the two elements compared together with its linguistic explanation and exact definition.

ANP formulates the problem in a network form such that different types of dependence are allowed; inner dependence, when elements of a cluster depend on each other, and; outer dependence, when different clusters of a network depend on each other. The fundamental scale for pair-wised comparison in ANP builds upon two main questions; (1) given a control criterion which of two elements is more dominant with respect to that criterion, and (2) which of two elements influences a third element more with respect to that 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, decreasing significantly the breach between model and reality.

Table 2.3 The Fundamental Scale for Pairwise Comparison

Importance Intensity	Definition	Explanation
1	Equal importance	Two activities contribute equally to the objective.
3	Moderate importance	Experience and judgment slightly favor one activity over another
5	Strong Importance	Experience and judgment strongly favor one activity over another
7	Very Strong importance	An activity is favored very strongly over another; its dominance demonstrated in practice
9	Extreme importance	The evidence favoring one activity over another is of the highest possible order of affirmation
2,4,6,8	Intermediate Values	
Reciprocals	If activity i is assigned one of the above nonzero numbers when compared with activity j, then j has the reciprocal value when compared with i	If the judgment is k in the (i, j) position in matrix A, then the judgment 1/k must be entered in the inverse position (j, i).

The use of pairwise comparison to formulate relations among variables helps directing attention to a given connection at a time, allowing a more precise and inclusive analysis. The simplification level needed to build hierarchy models requires an unusual effort to identify and handle multiple interconnections between components that a real problem has. In addition, ANP relies on the accumulated experience and knowledge of decision makers, instead of merely supplying them with data that may provide little decision support (Sarkis et al. 2006).

The priorities derived from pairwise comparison matrices are entered as parts of columns of a supermatrix. The supermatrix represents the influence priority of an element on the left of the matrix on an element at the top of the matrix with respect to a particular control criterion. An example supermatrix is shown in equation (2.8). The component C1 in the supermatrix includes all the priority vectors derived for nodes that are parent nodes in the C1 cluster.

$$W = \begin{array}{cc} & \begin{matrix} \boldsymbol{C_1} & \boldsymbol{C_2} & \cdots & \boldsymbol{C_N} \end{matrix} \\ \begin{matrix} \boldsymbol{C_1}\, e_{11} \\ e_{12} \\ \vdots \\ \boldsymbol{C_2}\, e_{21} \\ e_{22} \\ \vdots \\ \vdots \\ \boldsymbol{C_N}\, e_{N1} \\ e_{N2} \\ \vdots \end{matrix} & \begin{bmatrix} W_{11} & W_{21} & \cdots & W_{1N} \\ W_{21} & W_{22} & \cdots & W_{2N} \\ \vdots & \vdots & \cdots & \vdots \\ W_{N1} & W_{N2} & \cdots & W_{NN} \end{bmatrix} \end{array} \tag{2.8}$$

The unweighted supermatrix is constructed from the priorities derived from different pairwise comparisons. The column for a node contains the priorities of all the nodes pairwise compared with respect to it and influences it with respect to the control criterion. The weighted supermatrix is the multiplication of each entry in a block of the component at the top of the supermatrix by the priority of influence of the component on the left from the cluster matrix. Each column in the weighted supermatrix has a sum of 1, and thus the matrix is stochastic. The ANP then searches for steady state priorities from a limit super matrix. To obtain the limit supermatrix, the weighted matrix is raised to high powers. The limit of these powers, according to Cesaro Sumability, is equal to the limit of the sum of all powers of the matrix (Saaty 2001).

The steps of ANP model are outlined as follows (Saaty 2008):

1) Describe decision problem in detail including its objectives, criteria, attributes, and highlight the possible outcomes of that decision. Give details of influences to determine how the decision may come out.

2) Determine the control criteria, attributes, and obtain their priorities from paired comparisons matrices.

3) Determine the most general network of clusters (or components) and their elements that apply to all control criteria. Clusters and their elements should be numbered and arranged in a convenient way.

4) Determine clusters of the general feedback system with their elements, connect them according to their outer and inner dependence influences, for each control criterion, and sub criterion. An arrow is drawn from a cluster to any cluster whose elements influence.

5) Determine the approach to be followed in the analysis of each cluster or element, influencing other clusters and elements with respect to a criterion, or being influenced by other clusters and elements.

6) Construct the supermatrix by laying out clusters in the order they are numbered and all the elements in each cluster both vertically on the left and horizontally at the top for each control criterion. Enter in the appropriate position; the priorities derived from the paired comparisons are entered as sub columns of the corresponding column of the supermatrix.

7) Perform pairwise comparisons on elements within the clusters themselves according to their outer or inner dependence (influence on each element in another cluster they are connected to or on elements in their own cluster respectively). In making comparisons, one must always have a criterion in mind.

8) Perform paired comparisons on clusters with respect to the given control criterion. The derived weights are used to weight elements of the corresponding column blocks of the supermatrix. A zero is assigned in case of no influence.

9) Obtain the weighted column stochastic supermatrix.

10) Compute the limit priorities of the stochastic supermatrix.

11) Synthesize the limiting priorities by weighting each idealized limit vector by the weight of its control criterion.

2.9 FUZZY SETS THEORY AND FUZZY LOGIC

Fuzzy logic's main feature is the ability to operate on inaccurate data showing the most appropriate ways to deal with approximate reasoning rather than accurate. The Fuzzy set theory, first introduced by (Zadeh 1965), resembles the human reasoning in its use of approximate information and uncertainty to generate decisions. The fuzzy set theory models uncertainty caused by vagueness and imprecision of the human cognitive processes in real life systems. A crisp set is a set where an element either belongs to or does not belong to a set, in other words, its membership function is either 0 or 1. Fuzzy sets on the other hand allow partial membership; an element can belong to a set with any membership value ranging from (0) to (1). In a crisp set, the membership of an element x is described by a characteristic function $\mu_A(x)$, where;

$$\mu_A(x) = \begin{cases} 1 & \text{if } x \in A, \\ 0 & \text{if } x \notin A. \end{cases} \tag{2.9}$$

A fuzzy set theory expands this concept through defining partial membership, which can have values from 0 to 1. $\mu_A : x \rightarrow [0, 1]$

Where x refers to the universal set defined by the selected problem of interest. Therefore, for a set A with $x_0, x_1, x_2 \ldots x_n$. The fuzzy number is a special fuzzy set denoted as F= {(x, μ_f (x), x∈ R)}, where x takes values on the real line, $-\infty < x < +\infty$ and μ_f (x) is a continuous mapping from R to the closed interval [0, 1].

2.10 THE FUZZY ANALYTIC NETWORK PROCESS

In spite of the various advantages of ANP, the ANP-based decision model is noticeably ineffective when dealing with the inherent fuzziness or uncertainty in judgment during the pairwise comparison process. Even though using the discrete scale of 1–9 to represent the verbal judgment in pairwise comparisons has the advantage of being simple and straight forward, yet, it does not account for the uncertainty and imprecision associated with the mapping of a person's perception or judgment to a crisp number. In addition, in order to capture the expert's knowledge, it still cannot reflect the human thinking style (Kahraman et al. 2006).

In real-life decision-making situations, decision makers or experts could be uncertain about their own level of preference, due to incomplete information, insufficient knowledge, complexity, lack of appropriate measurement scale, or, uncertainty within the decision environment. Decision makers also tend to specify preferences in the form of natural language expressions which are most often vague and uncertain (Promentilla et al. 2008). Fuzzy logic is a natural way to incorporate the uncertainty or the 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 approximately satisfying the provided judgments.

Fuzzy AHP/ANP was introduced to capture the ‘fuzziness’ or the vague and uncertainty in the evaluation of alternatives. Human judgments are complex ones characterized by uncertainty and subjectivity that makes it sometimes unrealistic and infeasible to acquire exact judgments in pairwise comparisons. It is naturally easier to provide verbal judgments when giving subjective assessment. An expert may confidently claim that alternative A is strongly preferred than alternative B with respect to a control criterion but may fail to provide the exact ratio of how strongly A dominates B.

Fuzzy Linguistic Scale

Fuzzy logic is introduced to ANP mainly through adopting a fuzzy linguistic scale to pairwise comparison instead of the 9-point fundamental scale proposed by Saaty. The application of the linguistic scale however took several forms, the most used scales are those developed by (Cheng et al. 1999), (Kahraman et al. 2003), a fuzzy extension of (Saaty 1980) original scale, and, some self-defined scales (Etaati et al. 2011). Table 2.4 presents some of the fuzzy linguistic scales most widely used together with the number of terms and fuzzy sets utilized.

Table 2.4 Common Fuzzy Linguistic Scales (Adapted from (Etaati et al. 2011))

Authors	Fuzzy sets
(Cheng et al. 1999)	{(0,0,0.25);(0,0.25,0.5);(0.25,0.5,0.75);(0.5,0.75,1);(0.75,1,1)}
(Kahraman et al. 2003)	{(1,1,1);(0.5,1,1.5);(1,1.5,2);(1.5,2,1.5);(2,2.5,3);(2.5,3,3.5)}
(Saaty 1980)	{(1,1,1);(2,3,4);(4,5,6);(6,7,8);(8,9,10)}

Fuzzy prioritization methods

The concept of fuzzy AHP was extensively researched in literature and several fuzzy AHP models were introduced. The common methods used for prioritization include, Saaty's original Eigen Vector method, The Direct Least Squares Method (DLS) proposed by (Chu et al. 1979), Logarithmic Least Squares Method (LLS) also known as the geometric method (Crawford et al. 1985), goal programming method proposed by (Bryson 1995), and, Fuzzy Preference Programming Method (FPP) proposed by (Mikhailov et al. 2003).

Golany and Kress (1993) conducted a comparison analysis between the most commonly used methods of prioritization mentioned earlier and concluded there is no prioritization method superior to the other in all cases. They stated that all methods show advantages as well as drawbacks and the choice of prioritization method should be dictated by the objective of the analysis. This however was not the case for fuzzy ANP; most known interval and fuzzy prioritization methods derive interval or fuzzy priorities, which makes them difficult to apply in ANP due to the complex super matrix calculations (Mikhailov et al. 2003).

Several researchers introduced models for incorporating the fuzzy concept into ANP model. (Buyukozkan et al. 2004) applied a fuzzy ANP approach to quality-function deployment problems. They worked on the extension of the Fuzzy Analytical Hierarchy Process (FAHP) approach proposed by (Chang 1996). Their method derives crisp local priorities from fuzzy comparison matrix using extent analysis method and possibility theory. However, they used a rather simplified supermatrix calculation that appears to be far removed from that of the original ANP calculations. In addition, the algorithm they used sometimes yields a zero value of initial weights or local priorities to some elements of the decision structure. This might be problematic since a computed zero local priority (e.g. the importance weight of a criterion with respect to the goal) from the extent analysis implies some paths of interactions will not be considered in supermatrix calculations (Promentilla et al. 2008). However, it was noted by (Saaty 2001) that an unimportant element (in the essence of having the least local priority value) in a cluster may still show high levels of importance overall (of having the highest overall priority) because of dependence and feedback considered in the decision structure. Thus, Chang's method extension to the ANP framework has the major drawback of not capturing all possible interactions in the decision structure.

Cheng et al. (1994) developed a fuzzy-AHP-scale-based algorithm that used alpha-cuts, interval arithmetic, and linear convex combinations defined by optimism index values to transform the fuzzy comparison matrix into a set of crisp matrices; they then computed the set of crisp local weights from eigenvector of the matrix. Promentilla et al. (2008) extended the proposed algorithm for the use in fuzzy ANP. They used alpha-cuts, interval arithmetic and optimism index to transform the fuzzy comparative judgment matrix into set of crisp matrices, and redefined the fuzzy scale according to the degree of fuzziness, confidence level, and, attitude toward fuzziness. The desired priorities are then calculated using the eigenvector method.

Mikhailov & Singh, (1999) & (2003) addressed the problem through proposing the Fuzzy Preference Programming (FPP) technique which derives crisp priorities, including the criteria weight and the alternatives scores from crisp, interval and fuzzy judgments. Since the supermatrix priority-derivation process in ANP entitles complex matrix operations on real numbers, the most practical approach for incorporating the fuzzy concept into the ANP framework is by first deriving crisp weights or priorities from fuzzy comparison matrices. The FPP is applied to increase ANP capabilities in dealing with inconsistent and uncertain judgments through considering crisp comparison judgments as interval judgments with equal lower and upper bounds. In addition, 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).

2.11 THE FUZZY PREFERENCE PROGRAMMING

Fuzzy Preference Programming (FPP) adopts the concept of α–cuts to decompose fuzzy numbers into a number of intervals, adequately representing the initial fuzzy sets. The method finds priorities for each α-level cut, which are further aggregated in crisp local and global priorities (Mikhailov 2003).

Basic Concepts

Let A= (L_{ij}, U_{ij}) represent the interval comparison matrix with n components where L_{ij} and $U_{ij}$are the lower and the upper bounds of the corresponding uncertain judgments respectively. The FPP derives crisp priority vector *(w* $=(w_1, \dots, w_n)^T$) from interval judgments. Considering the interval judgments from the upper triangular part of matrix A, the priority vectors that satisfy the following inequalities can be generated because of consistent judgments.

$$L_{ij} \ll \frac{w_i}{w_j} \ll U_{ij}, \qquad (2.10)$$

Where*;* i= 1, 2, 3... n-1, and,

j = 1, 2, 3... n*, j*> i.

When the inconsistent judgment occurs, the double-side inequalities are introduced to satisfy all judgments as much as possible.

$$L_{ij} \lessapprox \frac{w_i}{w_j} \lessapprox U_{ij}, \tag{2.11}$$

Where; the notation $\lessapprox$, denotes the statement ‘‘fuzzy less or equal to’’.

The double-side inequalities are then linearized into a set of single-side linear fuzzy inequalities

$$W_i\text{-} W_j U_{ij} \lessapprox 0 \quad , \tag{2.12}$$

$$-W_i + W_j L_{ij} \lessapprox 0 \quad .$$

In total, there are n (n-1) fuzzy constraints as given in the following matrix form:

$$R_w \lessapprox 0 \quad , \tag{2.13}$$

Where the matrix R∈ $\Re^{m*n}$, m = n (n-1).

The k_{th} row of the previous equation ($R_w \lessapprox 0$), denoted by (R_k w) represents a fuzzy linear constraint and might be defined by a linear membership function of the type

$$\mu_k \text{ (R}_\text{k}\text{ w)}= \begin{cases} 1\text{-} \dfrac{R_k\, w}{d_k}, & R_k\, w \leq\ d_k, \\ \\ 0, & R_k\, w \geq\ d_k\ , \end{cases} \tag{2.14}$$

Where: d_k is a tolerance parameter for the k_{th} constraint of R_w, specified by the decision maker to provide a satisfactory solution of all judgments as much as possible and *k=1, 2, 3… m.* The value of the membership function μ_k *(R_k w)* represents the decision-makers’ satisfaction with the fulfillment of the single-side constraints. μ_k *(R_k w)* is equal to zero when the corresponding crisp constraint $R_k\ w \leq 0$ is strongly violated; μ_k *(R_k w)* is between zero and one when the crisp constraint $Rw \leq 0$ is approximately satisfied; and it is greater than one when the constraint is fully satisfied. The FPP method is based on two assumptions:

The first assumption; requires the existence of nonempty *fuzzy feasible area* $\tilde{P}$ on the simplex hyper plane Q^{n-1}, where;

$$Q^{n-1} = \{(w_1 \dots w_n) |\ w_i > 0, \sum_{i=1}^{n} w_i = 1\}. \qquad (2.15)$$

The membership function of the fuzzy feasible area is expressed in terms of the intersection of all interval membership functions in μ_k *($R_k w$)*, that is

$$\mu_{\tilde{P}}(w) = [min\ \{\mu_1 (R_1 w), \mu_m (R_m w)\} \mid w \in Q^{n-1}] \qquad (2.16)$$

The second assumption: specifies a selection rule, which determines a priority vector having the highest degree of membership in the aggregated membership function $\mu_{\tilde{P}}(w)$, since $\tilde{P}$ is a convex set, then there is always a priority vector *w* in Q^{n-1} that has a maximum degree of membership λ, therefore;

$$\mu_{\tilde{P}}(w) = \lambda = \max\ [\min\ \{\mu_1 (R_1 w) \dots \mu_m (R_m w)\} \mid w \in Q^{n-1}], \qquad (2.17)$$

The max-min prioritization problem presented above to obtain priorities can be represented as the following fuzzy programming problem:

$$\text{Max } \lambda \qquad (2.18)$$

Subject to $d_k\ \lambda + R_k w \leq d_k$ k=1, 2… m m= n (n-1)/2.

$\sum_{i=1}^{n} w_i = 1$, $w_i > 0$, i= 1, 2, 3… n

The optimal solution to this problem (w^*,λ^*) is a vector whose first component represents the priority vector that maximizes the degree of membership in the fuzzy feasible area, whereas its second component gives the value of that maximum degree $\mu_{\tilde{P}}(w^*) = \lambda^*$ is the consistency index which measures the degree of satisfaction and is a natural indicator for the inconsistency of the decision-makers' judgments. λ^* takes a value greater than or equal one when the human interval judgments are consistent, whereas for inconsistent judgments the consistency index (λ^*) takes a value between 0 and 1 depending upon the degree of inconsistency and the values of the tolerance parameters d_k (Mikhailov et al. 2003). It can be concluded that FPP transforms the prioritization problem into a linear program that can easily be solved by standard simplex technique. Two important notes should be considered when applying this method:

- All tolerance parameters can be set equal, since the decision-makers usually have no preferences about their specific pairwise comparison judgments.
- The values of the tolerance parameters if they are equal, do not affect the value of the maximizing solution w^*.

Decomposing Fuzzy Judgments Using α-cuts

When comparing two elements *Ei* and *Ej*, the exact numerical ratio a_{ij} can be approximated with a fuzzy ratio "abouta_{ij}", which is represented by a fuzzy number $\tilde{a}_{ij}$. The set of fuzzy comparison judgment provided by the decision maker F = $\{\tilde{a}_{ij}\}$ is equal to m≪ $\frac{n(n-1)}{2}$. The crisp sets of the ratios between the unknown crisp priorities $\{\frac{wi}{wj} \in X\}$ belonging to the fuzzy judgment $\{\tilde{a}_{ij}\}$ to degree of α are known as the *α-cuts of* $\tilde{a}_{ij}$. They are defined is equation (2.19);

$$\tilde{a}_{ij}(\alpha) = \{ \frac{wi}{wj} \in X \mid \mu_{\tilde{a}_{ij}}(\frac{wi}{wj}) \gg \alpha\} \qquad (2.19)$$

Consequently, by applying this concept, each fuzzy judgment $\tilde{a}_{ij}$ can be represented as a sequence of interval sets ($l_{ij}(\alpha_l)$, $u_{ij}(\alpha_l)$),

$$\tilde{a}_{ij}(\alpha_l) = (l_{ij}(\alpha_l), u_{ij}(\alpha_l)), \qquad (2.20)$$

Where; l=1, 2, 3… L

$0 < \alpha_1 < \alpha_2 < \cdots < \alpha_l$=1

Since the fuzzy judgments are normal convex fuzzy sets and in case of triangular fuzzy numbers, $\tilde{a}_{ij}$= (l_{ij}, m_{ij}, u_{ij}), the α-cuts are closed intervals such that; $a_{ij}(1) \subset a_{ij}(\alpha_{l-1}) \subset \ldots \subset a_{ij}(0)$, and $\tilde{a}_{ij}(\alpha_l)$ = ($l_{ij}(\alpha_l)$, $u_{ij}(\alpha_l)$), where; l_{ij}, u_{ij} are the lower and the upper bounds of the corresponding intervals. Therefore, through applying α-cuts, the initial set of fuzzy comparisons F = $\{\tilde{a}_{ij}\}$ is converted to a set of L interval sets $F_L = \{a_{ij}(\alpha_l)\}$, l=1, 2, 3… L

Aggregating Priorities

Through decomposing fuzzy judgments using α-cuts and applying FPP method, a sequence of crisp priorities $W(\alpha_1)$, corresponding to each α-cut level can be obtained; the results are then aggregated to find final crisp values of priorities.

$$W(\alpha_1) = (W_1(\alpha_l), W_2(\alpha_l) \ldots W_n(\alpha_l))^T \quad (2.21)$$

l=1, 2, 3… L $\qquad 0 = < \alpha_1 < \alpha_2 < \cdots < \alpha_l$=1

The α value is regarded as the degree of confidence the decision maker shows over his judgments (Mikhailov 2003). While a smaller value of α implicates a high level of uncertainty and less trustworthy assessments due to its large spread, a greater value of α provides a narrower spread and thus a lower uncertainty level. When triangular fuzzy numbers are used to represent fuzzy judgment, an α-cut value of one entails a crisp judgment equals to m_{ij}, which is the most possible value of the fuzzy comparison membership function $\tilde{a}_{ij}$= (l_{ij}, m_{ij}, u_{ij}). Consequently, the value of α can be used as a weighting factor of the solutions such that the value of priorities can be aggregated using the weighted sum equation as seen in equation (2.22);

$$w_j = \frac{\sum_{l=1}^{L} \alpha_l \, w_j(\alpha_l)}{\sum_{l=1}^{L} \alpha_l} \qquad j=1, 2, 3 \ldots n \qquad (2.22)$$

Where w_j denotes the aggregated weight of the *j-th* priority.

Non-Linear Fuzzy Prioritization

Mikhailov (2003) also developed a non-linear fuzzy prioritization model to obtain directly crisp values of priorities from a set of comparison judgments, represented as triangular fuzzy numbers. The crisp priority vectors are computed such that they approximately satisfy the initial fuzzy judgments $\tilde{a}_{ij} = (l_{ij}, m_{ij}, u_{ij})$ as indicated in equation (2.23);

$$L_{ij} \mathrel{\tilde{\ll}} \frac{W_i}{W_j} \mathrel{\tilde{\ll}} U_{ij}, \qquad (2.23)$$

The non-linear method develops a membership function for each fuzzy judgment that is linear with respect to $\frac{W_i}{W_j}$

$$\mu_{ij}\left(\frac{W_i}{W_j}\right) = \begin{cases} \dfrac{(\frac{W_i}{W_j} - L_{ij})}{m_{ij} - L_{ij}}, & \frac{W_i}{W_j} \ll m_{ij}, \\ \\ \dfrac{(u_{ij} - \frac{W_i}{W_j})}{u_{ij} - m_{ij}}, & \frac{W_i}{W_j} \gg m_{ij}. \end{cases} \qquad (2.24)$$

This membership function is linearly increasing over the interval $(-\infty, m_{ij})$ and linearly decreasing over the interval (m_{ij}, ∞). The function has negative values when $\frac{W_i}{W_j} < l_{ij}$, or $\frac{W_i}{W_j} > u_{ij}$, and it reaches its maximum value of $\mu_{ij} = 1$ when $\frac{W_i}{W_j} = m_{ij}$. The membership function

$\mu_{ij}\left(\frac{W_i}{W_j}\right)$ coincides with the fuzzy triangular judgment $\tilde{a}_{ij} = (l_{ij}, m_{ij}, u_{ij})$ over the range (L_{ij}, U_{ij}). When applying the max-min approach for acquiring the solution, the non-linear optimization problem presented in equation (2.25) is created;

$$\text{Max } \lambda \tag{2.25}$$

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

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

$\sum_{k=1}^{n} w_k = 1, \qquad w_k > 0, \qquad k = 1, 2, 3 \ldots n$

$i = 1, 2, 3 \ldots n-1, \qquad j = 2, 3 \ldots n, \qquad j > i$

The optimal solution to the non-linear problem above (w^*,λ^*) is obtained by employing numerical method for non-linear optimization. If the optimal value of λ^* is positive, this indicates all solution ratios satisfy the fuzzy judgment completely, which means that the initial set of fuzzy judgments is rather consistent. Alternatively, a negative value of (λ^*) shows the solution ratios approximately satisfy all double-side inequalities. Therefore, the optimal value λ^* can be used for measuring the consistency of the initial set of fuzzy judgments.

The process of applying Fuzzy ANP using FPP can be summarized in the following main steps:

- Decompose the decision problem to construct a hierarchical or network structure including clusters, criteria, attributes, lower elements, and, alternatives,
- Highlight dependences among all components of the above structure and define the impact between each,

- Construct pairwise comparison matrices of components with crisp, interval, or, fuzzy ratio judgments,
- Perform FPP on each comparison matrix individually to derive each set of local priorities,
- Form an unweighted supermatrix with the derived local priorities from previous step,
- Produce the weighted supermatrix by adjusting the supermatrix to column stochastic,
- Find the limit supermatrix with a sufficiently large power number to converge into a stable supermatrix,
- Obtain the final priorities via aggregating weights of criteria and scores of alternatives.

FANP handles the uncertainty in quite a different manner than that of regular ANP with sensitivity analysis. Fuzzy ANP accommodates the subjectivity of human judgment as being expressed in natural language which entails 'fuzziness' in real-life problems. It should be clear however that an obvious difference exists between 'fuzziness' in human judgment within the framework of ANP and the traditional concept of 'inconsistency' in judgment. The inconsistency in judgments is measured by the consistency ratio (CR) proposed by (Saaty 2001), to test the reliability of the decision outcomes. If the computed CR is more than 0.10, the expert is asked to reconsider and revise his judgment to improve the consistency according to his understanding. Higher values of CR imply that inconsistency occurs because of some 'errors in judgment' on the part of the expert. Some of the causes of inconsistency may be lack of information, lack of concentration during judgment process, and, inadequate model structure.

2.12 FUZZY INFERENCE ENGINE

A fuzzy inference system is designed based on the past known behavior of a system and is then expected to reproduce the system behavior (Ross. 2010). This concept have been applied to many disciplines including data classification, decision analysis, computer vision, and, expert systems. Fuzzy inference systems are usually defined using different terminologies such as fuzzy-rule-based systems, fuzzy associative memory, fuzzy logic controllers, fuzzy expert systems, and fuzzy modelling (Ross, 2010). The first fuzzy control model was introduced by Mamdani et al. (1975) to control a steam engine and boiler combination by synthesizing a set of linguistic control rules obtained from experienced human operators. Fuzzy proposition or fuzzy inference engines are important application of fuzzy logic. A typical fuzzy inference system (FIS) as shown in Figure 2.1 includes four main processes (1) fuzzification, (2) Knowledge base, (3) fuzzy inference system, and (4) defuzzification.

1. Fuzzification

Fuzzification is the process of transforming crisp values into grades of membership functions for linguistic terms of fuzzy sets. Membership functions are used to associate a grade to each linguistic term. In this step, the input values (crisp values) are translated into linguistic terms such as high, medium, and, low using different types of membership functions depending on the modeled problem, experts' knowledge and contexts (Alvarez Grima, et al. 2000). The model input is a crisp numerical value limited to the universe of discourse to the input variables (usually between 0 and 1). Whereas the output is a fuzzy degree of membership in the specified linguistic set. Membership functions vary from linear membership functions such as triangular and trapezoidal, to nonlinear membership functions such as Gaussian, bell shaped or S-shaped functions. Linear membership functions are mostly selected for input and output variables in engineering domain due to their simplicity and computational efficiency (Ross, 2010).

2. **Knowledge Base**

Fuzzy modelling takes advantage of domain knowledge through incorporating human expertise directly in the modelling process. The knowledge acquisition stage is required to understand and develop relationships between antecedents and consequents. Knowledge acquisition is done through preliminary analysis, literature review, surveys, questionnaires, and, interviews with industry experts. As seen in Figure 2.1, the knowledge base is composed of fuzzy sets or membership functions representing the data base and fuzzy rules composing the fuzzy propositions.

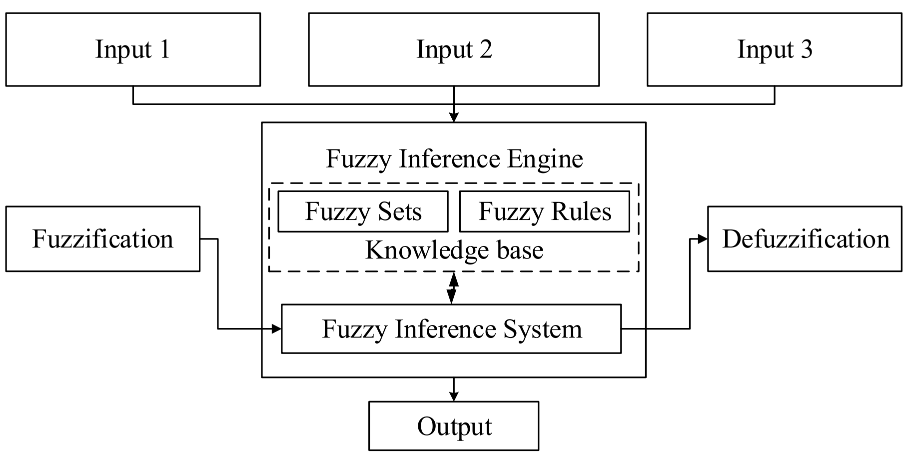


Figure 2.1 Fuzzy Inference Engine

Fuzzy propositions are statements having fuzzy variables and used to describe the input-output relationships using fuzzy if-then rules. These fuzzy rules are extracted from experts' judgments, engineering knowledge and experience (Ghasemi & Ataei, 2012). A fuzzy rule typically takes the form IF premise (antecedent) THEN conclusion (consequent) for instance "if x is high (premise) then y is Critical (consequent)" where the terms high and critical are represented by membership functions (Jang et al., 1997).

3. Fuzzy Inference System (FIS)

The fuzzy inference unit uses fuzzy If Then rules to assign a map from fuzzy composition rules using fuzzy inputs and fuzzy outputs (Li, 2006). This is the major step in a fuzzy expert system where rules are aggregated and the modelling process is done. The main variance between different fuzzy inference systems lies in the consequent of rules, and accordingly, the aggregation and defuzzification processes differ (Ghasemi & Ataei, 2012). The most commonly used FIS are: the Mamdani fuzzy model, the Takagi–Sugeno–Kang (TSK) fuzzy model, and, the Tsukamoto fuzzy model. The Mamdani model is known for its simplicity, it uses concepts from fuzzy logic and sets to translate a set of unstructured linguistic heuristics into an algorithm (Mamdani & Assilian, 1975). The rule form of the Mamdani algorithm is shown in equation (2.26)

If x_1 is A_{i1} and x_2 is A_{i2} and ….. x_r is A_{ir} then y is B_i (for i = 1, 2, 3 …k) (2.26)

Where;

x_i is the input variable,

A_{ir} and B_i are linguistic terms defined by fuzzy membership functions,

y is the output variable, and,

k is the number of rules.

For cases where the antecedent has more than one part, the fuzzy operator is applied to obtain one number representing the consequence for the antecedents of that rule. This is the number used afterwards to obtain the output function. The Mamdani FIS uses the min-max composition defined in equation (2.27)

$$\mu_{C_K}(Z) = \max\left[min\left[\mu_{A_K}\left(input\ (x)\right), \mu_{B_K}\left(input\ (y)\right)\right]\right] k \tag{2.27}$$

Where;

μ_{C_K} ,μ_{A_K} μ_{B_K} are the membership functions for output “z” for rule “k”

X and y are inputs.

4. **Defuzzification**

Defuzzification is the process by which fuzzy sets are transferred into crisp values. Defuzzification methods are numerous including the Centroid of Area (COA), Bisector of Area (BOA), Mean of Maximum (MOM), Largest of Maximum (LOM), and Smallest of Maximum (SOM). The COA method, most commonly used, has the advantage that all activated membership functions of the conclusions (all active rules) take part in the defuzzification process. The COA method applies Equation (2.28) for transferring fuzzy scheme into a crisp value, it is similar to calculating the expected value for a probability distribution:

$$COA = \frac{\int_z \mu_A(z) z\, dz}{\int_z \mu_A(z)\, dz} \tag{2.28}$$

Where; $\mu_A(z)$ is the aggregated output membership function.

Fuzzy Membership Function

The choice of membership function and its representation remains one of the challenges of fuzzy logic. The literature demonstrates six basic methods for constructing membership functions (Bilgiç & Türkşen, 2000); Polling, in which the question is presented as a poll to different experts. Their answers are averaged to conclude the membership function. Direct rating (point estimation) is the simplest and most straight forward method to compute membership functions. Reverse rating; for a given membership degree, the expert is asked to identify the object for which that degree corresponds to the fuzzy term in question. Interval estimation (set valued statistics): the expert is asked to provide an interval for the fuzzy membership function, Membership function exemplification and pairwise comparison are the last two methods used. The method used to develop membership functions depends mainly on the problem identified at hand and the availability of sources.

Triangular Fuzzy Number

Triangular fuzzy numbers (TFN) are a special form of linear fuzzy number denoted as $\widetilde{M} = (l, m, u)$, where; $l \ll m \ll u$, and they refer to the lower, moderate, and upper values of the membership function respectively. It has the triangular-type membership function expressed in equation (2.29):

$$\mu_{\widetilde{M}}(\mathrm{x}) = \begin{cases} 0, & x < l, \\ \frac{x-1}{l-1}, & l \ll x \ll m \\ \frac{u-x}{u-m}, & m \ll x \ll u \\ 0, & x > l. \end{cases} \tag{2.29}$$

2.13 INFRASTRUCTURE BUDGET ALLOCATION

Government agencies are required to make intelligent decisions for which projects to be funded and the degree of funding to ensure maximum benefits from the limited funds (Zayed 2004).

Infrastructure budget-allocation problems vary in complexity from simple project exercises to project level optimization. In case of infrastructure-level budget allocation, the budget allocation problems are complex in which the solution set is limited for each element but is huge for the entire network. The optimal or near optimal solution in this case is the combination of the sub-element solutions (Al-Battaineh 2007). Several methods were utilized for infrastructure budget-allocation problems that vary in their characteristics and ability in producing optimum or near-optimum solutions.

Abraham et al. (1998) developed a deterministic dynamic programming optimization model to identify appropriate sewer rehabilitation techniques at different stages of the planning horizon. The budget allocation method used is a rule-based process in which each pipeline is modeled within a time interval of 5 years. The appropriate rehabilitation action was selected depending on each pipe state and the benefit/cost ratio assessed by means of expert opinions. This method proved useful when dealing with a small number of pipe sections with unconstrained budget. (Lee et al. 2004) provided decision makers with a practical tool for roads and streets prioritization of cost-effective Maintenance and Repair (M&R) alternatives. They developed a set of preliminary M&R criteria based on pavement rank, minimum Pavement Condition Index (PCI) values computed by MicroPAVER program using visual inspection data of roads in the network, and, construction constraints. The optimal M&R strategies were then selected to perform a preliminary budget analysis. This model provided two alternatives of five-year M&R plans for the town council's consideration. On the other hand, Guignier and Madanat (1999) developed a Markov decision model for the joint optimization of maintenance and improvement, thus improving the budget allocation among facilities in the network between two sets of activities and within each set. Sadek et al. (2003) designed an integrated infrastructure management system to manage the needs of six different components of a transportation system. This framework used Solver to determine the budget allocation among the competing needs of the different transportation components. Gabriel et al. (2006) developed a network-level budget allocation model for infrastructure projects. Their model aimed to minimize the total expected cost while maximizing the total value of the selected projects within the available budget using a weighting method to select the Pareto optimal points. Moselhi et al. (2010) developed a four-phased level of service driven reliability-based methodology for budget allocation of water mains. The model considered the network level of service, sub-network reliability, and, criticality for the budget allocation calculations. Mohamed and Zayed (2012) developed a fund allocation index (priority index) for water mains to assist municipal engineers in effectively allocating available funds to candidate projects. The index was developed using an integrated AHP/MAUT and simulation approaches based on the judgment of municipal engineers/experts from across Canada and USA (Mohamed and Zayed 2013).

Genetic Algorithms (GA) played an important role in optimization problems due to their known ability to reach near-optimum solutions to large problems. Perng et al. (2007) used GA in the optimization of budget allocation for historical buildings in Tainan City, Taiwan. The mathematical optimization of infrastructure investment decision model developed by Hsieh et al. (2004) used GA to maximize the investment utility under the conditions of multiple alternatives (each comprising a set of subprojects), and multiple objectives with time-logic and resource constraints. AL-Battaineh et al. (2005) used GA to develop a model for the budget allocation of infrastructure systems on a network level. The model's optimization objective is maximizing the system performance index by finding the optimum allocation of available budget for the system under consideration. Hegazy (1999) used GA to develop a model that minimizes the total project cost as an objective function while considering specific project constraints for time and cost. Liu et al. (1997) used GA in the multi-objective optimization of bridge-deck rehabilitation problem while minimizing the total rehabilitation cost and degree of deterioration. Chan et al. (1994) used GA to develop a road-maintenance planning model. Farran and Zayed (2012) developed a life-cycle cost maintenance and rehabilitation planning methodology for public infrastructure based on a dynamic Markov chain with directed-GA optimization techniques. The method was developed for a single facility and allowed determining the optimal sequence of M&R actions over a desired study period.

2.14 GENETIC ALGORITHMS

Optimization decisions in the construction industry involve maximization or minimization problems subject to a number of conditions that influences the decision. Defining and evaluating the set of all feasible solutions, while considering problem constraints and conditions, becomes complicated specially with the increase in number of solutions (Al-Tabtabai et al. 1999). Mathematical programming methods such as linear programming, integer-linear programming, and, goal programming are popular tools used for optimization decisions. However, these methods call for over-simplifying the problem to make them possible to solve using mathematical methods. In addition, the solution time for these methods tends to grow exponentially as the number of decision variables increases because of the combinatorial nature of the problem (Chandra 1991). While it is relatively simple to determine solutions to small problems through present mathematical techniques, it is not a realistic approach to the problem. Conversely, evolutionary-based algorithms demonstrate high ability to reach optimum or near-optimum solutions to large combinatorial problems such as optimization problems (Morcous et al. 2002).

Evolutionary based algorithms were developed to search near-optimum solutions to problems with large number of variables and non-linear objective functions. Evolutionary Algorithms (EAs) are stochastic search methods that imitate the metaphor of natural biological evolution and/or social behavior of different species. Genetic Algorithms (GA), developed by John Holland (1975), are one of the first EA introduced in the literature. GA mimics the Darwinian principle of the 'survival of the fittest' and the natural process of evolution through reproduction. GA use information from experience to evolve solutions to real-world problems, once they are appropriately encoded. This adaptive search technique, having powerful non-linear processing capabilities, can be used to solve multi-dimensional optimization problems with discrete variables and discontinuous functions (Al-Tabtabai et al. 1999).

Genetic Algorithms Operation

GA work with a population of individuals each representing a possible solution to a given problem. Each candidate solution, or individual, is generally represented as a string of genes analogous to chromosomes and genes in the evolution theory. Through assigning a fitness score to each individual based on the quality of the solution it represents, highly fit individuals are reproduced though cross over and mutation with other individuals. The cross over mixes the parents' information, which is then, passed to the children chromosomes. Mutation on the other hand, introduces information that is not existent in parents and passes them to the children chromosomes. Through a randomized process, new populations are continuously evolved over generations. The population is expected to converge finally towards an optimal solution to the encoded problem after a certain number of generations are reached. Figure 2.2 illustrates the basic GA operations.

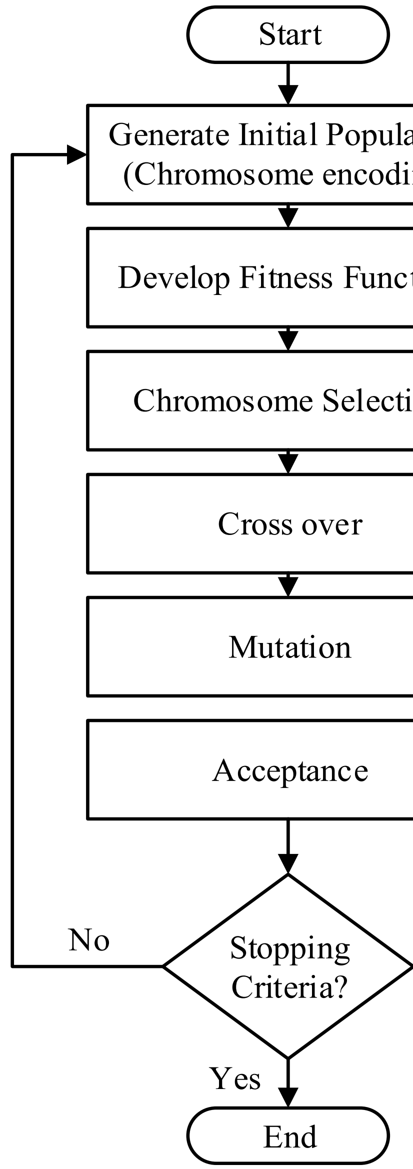


Figure 2.2 Basic Genetic Algorithm Flowchart

Chromosome Encoding

GA works on chromosomes of binary, permutation, value, tree, or, any set of encoding that serves the problem. Chromosomes encoding vary in complexity based on the problem requirements and development. The required information to assemble the solution is built in the chromosome encoding.

Fitness evaluation

Fitness evaluation is a measure of the chromosome's efficiency for meeting the objectives of the problem. The fitness function is designed to reflect the value of the chromosome in some "real" manner (Beasley et al. 1993). The information in each chromosome is passed to the fitness function as an input to evaluate the efficiency of the current chromosome in meeting the objectives of the problem. A fitness value is then assigned to the chromosome to represent its fitness. The higher the fitness value assigned, the better is the chromosome.

The algorithm has no pre-knowledge of the problem being solved. The only information provided to the chromosome is the fitness of each chromosome in the population. The fitness evaluation is based upon the knowledge collected through answering the question "what makes a solution superior to other".

Genetic Algorithms Operators

The selection operator is performed on the current population to select parents for the next generation. This operator selects good strings in a population and forms a mating pool for better results in crossover and mutation. Various selection schemes are used such as the roulette-wheel selection, tournament scheme, stochastic remainder selection, etc. (Chong et al. 2004). The Roulette-wheel is a common stochastic procedure that correlates the probability of selection for each chromosome to its fitness value (Morcous et al. 2005); it is the most widely used method of selection. For a specific chromosome, the probability of choosing it as a parent for the next generation equals to its fitness value divided by the cumulative fitness of the current population. This results in chromosomes with higher fitness values having a better chance to be selected as parents for the next generation. On the other hand, a low number of chromosomes having low fitness value will also be selected as parents for the next generation. The selection process starts by ranking the chromosomes based on their fitness. The weighted rank score is then evaluated and a probability associated with a length on the roulette-wheel is assigned. The selection process is executed by generating a random number $x \in [0, 1]$, then selecting the chromosome that holds the number x.

The evolution process works by means of two operators: crossover and mutation. Crossover is a recombination operator that proceeds in three steps: the reproduction operator selects at random a pair of two individual strings for mating, a cross site is selected at random along the string length, and, the position values are exchanged between the two strings following the cross site. One-point cross over is the simplest form of cross over. In which, for every pair of chromosomes with length L, a random point along L is chosen, resulting in dividing each of the parents into two parts. The corresponding parts are swapped between the chromosomes resulting in two new offspring chromosomes. The two-point cross over is the process in which two random points are selected along the chromosome length L. The genetic material across these two points is swapped to produce two offspring chromosomes. Mutation is the genetic operator responsible for changing the chromosomes genes with a certain probability. Mutation prevents the algorithm from becoming trapped in local optima and plays the role of introducing genetic diversity into the new generation. The mutation rates are kept low to resemble the natural process, for a chromosome of length L, the mutation rate is recommended as 1/L. When applying mutation to a bit string, it sweeps down the list of bits of that chromosome while replacing each by a randomly selected bit if the probability test of that bit passes. Mutation is applied through substituting the value of the passing bit by a randomly generated value within the range acceptable.

The three operators are performed until a stopping criterion is met. The criterion is usually reaching a specific number of generations, minimum improvement in the average fitness, or, computation time. Based on the literature review, GA are successfully used in optimizing complex combinatory problems and proved superiority in modeling logical constraints.

2.15 SUMMARY

This chapter started by studying the different practices and research works developed in the subway network area. Current practice adopted by public authorities is considered a black box where authorities rely on ‘blind’ periodic inspection and the ‘know-how’ of maintenance staff to schedule maintenance actions required. The literature presented demonstrates that even the models used to assess subway networks for rehabilitation rely mainly on subjective and customer driven criteria while neglecting operational failure of networks. On the other hand, the models developed in academic context had several limitations. First, none of the models available addressed the network from a functional perspective, literature models only focused on the structural side of a network. Second, the available structural models addressed the subway from an asset level rather than a network wide level. Third, none of the available models attempted to measure or analyze the risk level of the network. And last, no attempted efforts are found to optimize fund spending on a network wide level.

On the other hand, several network-wide models developed for other infrastructures such as pipelines and bridges are presented. These models demonstrate the importance of a network-wide level assessment, whereas risk assessment of networks cannot be over emphasized. The presented literature highlights the serious lack existent in the subway network area. Thus triggering the current research to develop a model that measures, analyzes, and integrates structural and functional aspects in a network and use them to develop a risk index and optimize the network performance.

Subway networks are characterized by two main characteristics; they are complex systems composed of a large number of interconnected components showing different behaviors, and the inspection of a subway networks is an irregular task, only few inspections are done in the subway history. Considering these characteristics, none of the practices or models addressed in the literature assessed the consequence of failure of subway networks or their station criticality. The developed systems lack integration between a deterioration prediction model, a repair selection option, and network optimization scheme along a planning horizon. In other words, none of the models can be used to develop a comprehensive model for the prioritization of the subway elements for rehabilitation while considering structural and functional network aspects.

CHAPTER 3. METHODOLOGY

3.1 METHODOLOGY OVERVIEW

This chapter presents the framework followed to develop a risk-based budget allocation model for subway networks. A total of three sub-models and two main models are developed. Firstly, sub-models for measuring components of a classical risk equation, namely, probability and consequence of failure, are developed. The third sub-model is the criticality index which is an addition to the classical risk equation proposed in this research to better accommodate subway networks. The three sub-models are integrated using fuzzy inference systems into a global comprehensive risk model. The output of the risk model, that is a risk index, is combined with suggested rehabilitation actions into a budget allocation model. The methodology adopted is illustrated in figure 3.1 and outlined in five main steps as follows:

- Develop a probability of failure sub-model to compute the expected probability of structural failure of various components in a subway network.
- Estimate failure consequence of different elements per stations by means of a consequence of failure sub-model,
- Calculate the criticality index for each station using the criticality index sub-model,
- Integrate the three sub-models into a global risk index model, this model provides the forecasted risk index of subway stations.
- Use the developed risk index as an input for the budget allocation model together with the rehabilitation options and maintenance costs.

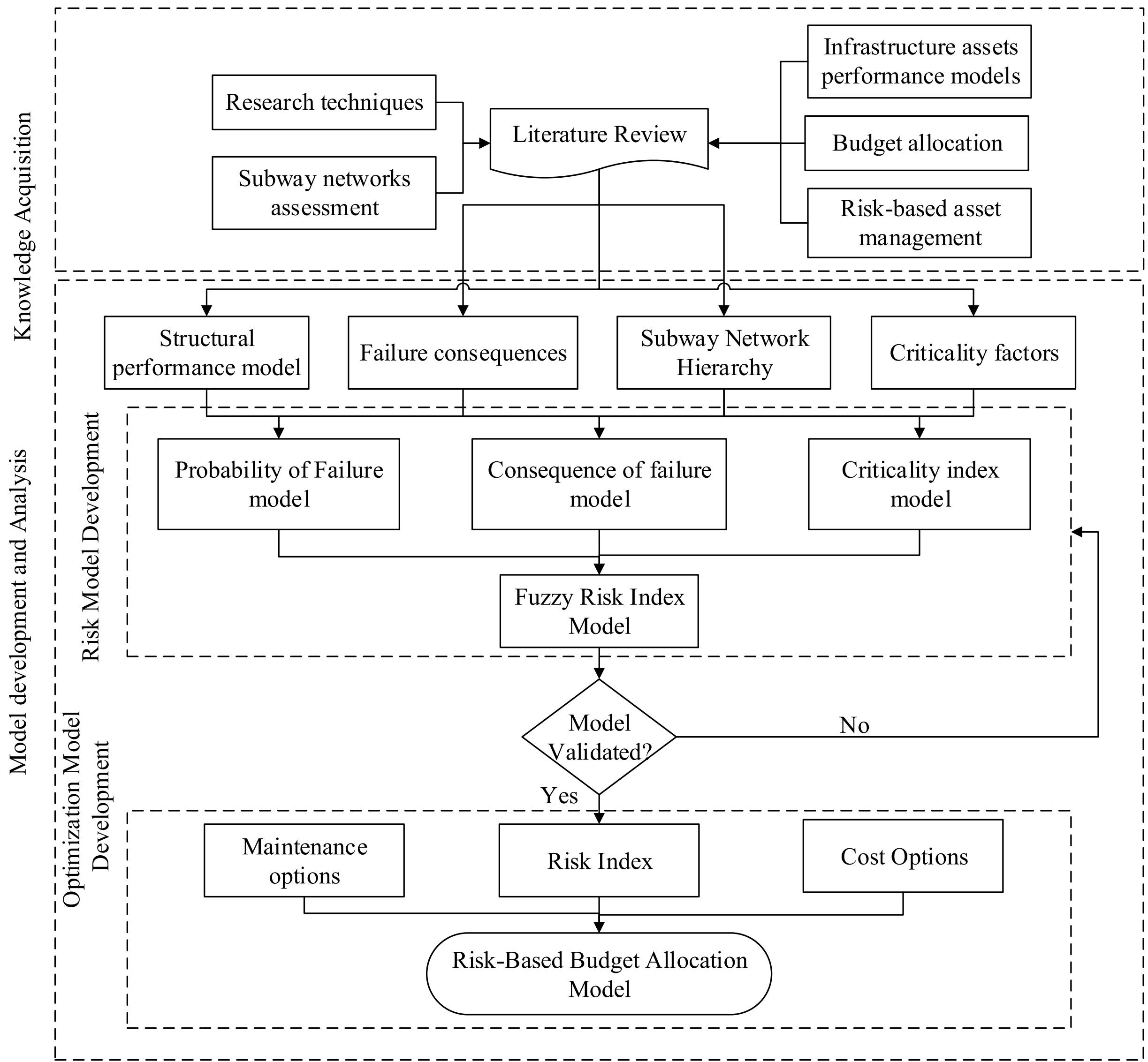


Figure 3.1 Research Methodology Overview

3.2 SUBWAY NETWORK HIERARCHY

The first step in developing a network model is breaking down the infrastructure into its building components and elements to facilitate the computation and analysis process and ensure no lower elements are ignored in the analysis. Accordingly, a generic subway network is proposed as seen in Figure 3.2. A typical subway network is composed of a number of interconnecting lines, each composed of station buildings that operate by means of their composing systems; mechanical, structural, electrical, and, security and communication. This research focuses only on the operational risk failure derived from the structural systems in a network. Therefore, the structural system is identified as a composition of stations, tunnels and auxiliary structures. These are composed of the elements located at the lowest level of the hierarchy. This hierarchy will be the basis of calculations through model development and its associated sub-models. However, each sub-model operates on a different level of the hierarchy and the risk index model is generic for all levels.

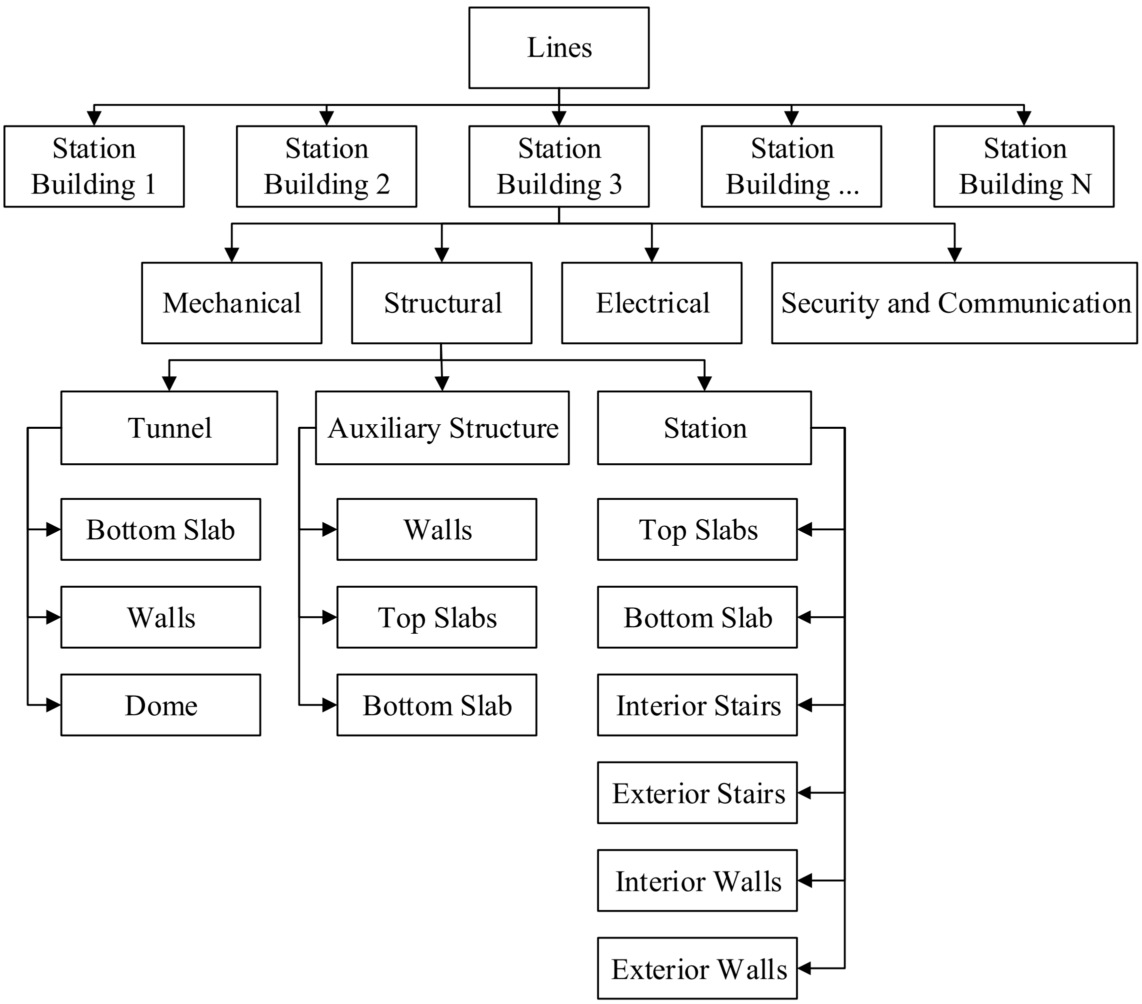


Figure 3.2 Proposed Subway Network Hierarchy

3.3 THE PROBABILITY OF FAILURE SUB-MODEL

The first sub-model to be developed is the Probability of Failure (PoF) sub-model. Figure 3.3 illustrates the steps of the probability of failure sub-model used to compute probability of failure for network elements, systems, and, up to the entire network. The reliability of each element is computed using the model proposed by Semaan (2011), furthermore, the curves are updated to the year 2014 and to include any rehabilitation actions undertaken since the model development.

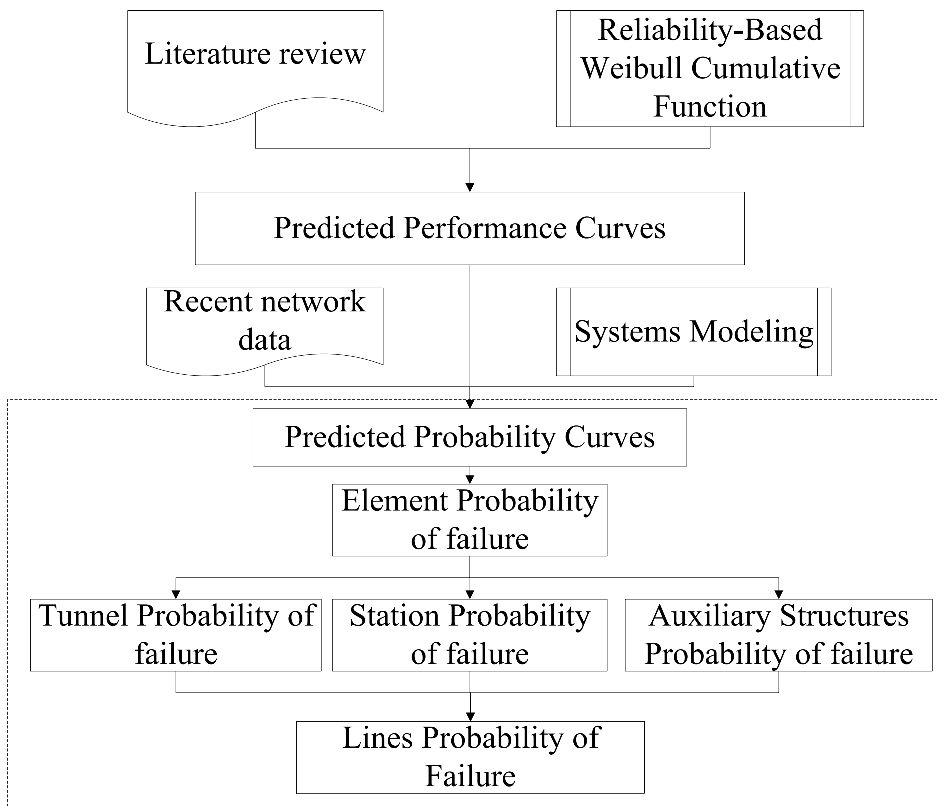


Figure 3.3 Probability of Failure Sub-Model Outline

Reliability-based cumulative Weibull function takes a probabilistic approach that yields a reliability index, which is the inverse of probability of failure. Therefore, probability of failure can be estimated as the inverse of the reliability and is shown in Equation (3.1):

$$\text{PoF} = 1 - R(t) = 1 - e^{-\left(\frac{t-\alpha}{\tau}\right)^{\delta}} \tag{3.1}$$

Where,

R (t) = Reliability, t = Time, δ = deterioration parameter, α = location parameter, τ= scale parameter, and e = exponential function.

Different system configuration requires different calculations for probability of failure values. The parallel-series network modeling technique (Hillier, et al., 1972) entitles that any system is composed of components outlined in parallel, in series, or, in a combination of both. A system in parallel is a redundant system where components work simultaneously; it can operate even if one of its components fails. Probability of a parallel system failure is shown in equation (3.2)

$$\text{P [system failure]} = \prod_{i=1}^{n} P_i \tag{3.2}$$

Where, i=1, 2, 3 …n = independent components composing a system,

P_i= Probability of failure of a single component

Systems in series on the other hand operate efficiently if all its components are operating efficiently. Therefore, probability of failure of a system with n components in series is computed as shown in equation (3.3)

$$\text{P [system failure]} = 1 - \prod_{i=1}^{n}(1 - P_i) \tag{3.3}$$

Following the subway hierarchy proposed earlier, probability of failure values are computed for elements at the lowest level of the hierarchy and then aggregated upwards using the parallel-series network modeling technique to systems, building stations, and, lines level. The following assumptions are considered when constructing the reliability and probability of failure equations;

1. The ideal Service Life (SL) is assumed 100 years for all infrastructure concrete elements.
2. The performance threshold equals 2/5=0.4
3. The minimum performance is equal to 1/5 = 0.2
4. The failure rate is defined as $\frac{1}{\tau}$, or the inverse of the service life adjustment parameter.

Station System (STA)

In a subway station system, the slab and stairs are redundant systems and can be considered as parallel systems since failure of one component does not entail failure of the entire system. The wall system however, is a series system in which if any wall "fails" to perform, the whole station becomes unsafe, and thus does not perform. Probability of failure of a station system can be computed using equation (3.4)

$$P_{STAj} = 1- [(1- \prod_{i=1}^{n} P_{STEi}\, P_{STIi})*(1- \prod_{i=1}^{n} P_{SEi}\, P_{SIi})*(1- \prod_{i=1}^{n}(1 - P_{WIi})(1 - P_{WEi}))] \qquad (3.4)$$

Where,

P_{STAj} = Probability of station j failure, P_{STE} = Probability of exterior stairs failure, P_{STI}= Probability of interior stairs failure, P_{SE}= Probability of external slab failure, P_{SI}= Probability of internal slab failure, P_{WI}= Probability of internal wall failure, P_{WE}= Probability of external wall failure, and, i=1, 2 … n = station floor, j=a, b, c…k.

Tunnel System (TUN)

A tunnel system is composed of three main elements, a dome, walls, and, a bottom slab. These three elements operate in series in which one element failure translates into an entire system failure. This can be seen in the probability of failure values calculated in equation (3.5)

$P_{TUN} = 1 - (1 - P_D) * (1 - P_w) * (1 - P_s)$ (3.5)

Where; P_{TUN} = Probability of tunnel failure, P_D = Probability of Dome failure, P_w = Probability of wall failure, P_s = Probability of slab failure.

Auxiliary Structures System (AUX)

Auxiliary structure operates in series in which it fails if any of its components fail, therefore, probability of failure is calculated using equation (3.6)

$P_{Aux\ St} = 1 - (1 - P_w)\ (1- P_{TS} * P_{BS})$ (3.6)

Where;

P_{AuxSt} = Probability of auxiliary structure failure, P_W = Probability of walls failure, P_{TS} = Probability of top slab failure, and, P_{BS} = Probability of bottom slab failure.

Line System

A generic subway network line is composed of all stations, tunnel, and auxiliary structure systems operating on the line. These systems together operate in series whereas; the composition of each system operates in parallel. The stations systems are redundant system, they operate in parallel and will fail to operate when all stations in a line fail. Likewise, a line failure occurs when all tunnels on the line fail to operate. Same applies for the auxiliary structure, operating is parallel in a line system. On the other hand, the three systems operate in series. If any of the systems fails entirely that means the subway line is in a failure status and can no more function effectively. The line systems operation scheme is seen in Figure 3.4 and computed using equation (3.7);

$P_{line\ z} = 1 - [(1 - \prod_{i=1}^{n} P_{STA_i}) * (1 - \prod_{i=1}^{n} P_{TUN_i}) * (1 - \prod_{i=1}^{n} P_{AUX_i})]$ (3.7)

Where;

P_{line} = Probability of line failure, P_{STA} = Probability of station failure, P_{TUN} = Probability of tunnel failure, $P_{Aux\ St}$ = Probability of auxiliary structure failure, and i=1, 2 … n = number of systems in a line.

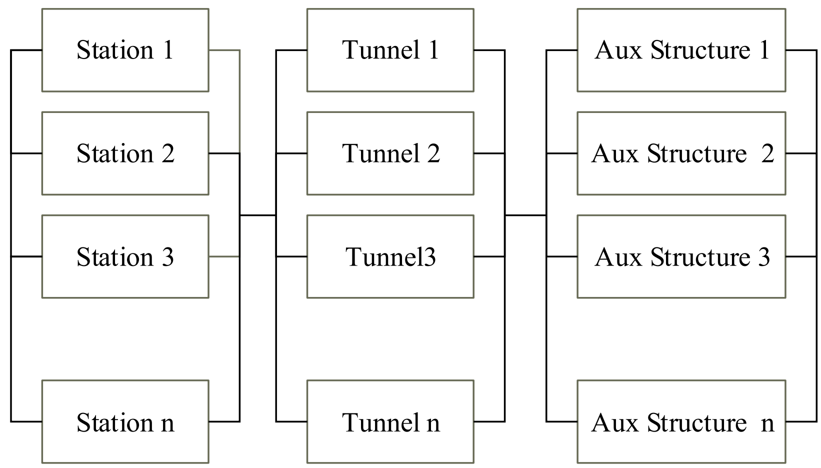


Figure 3.4 Schematic Diagrams for Systems in Operation in a Network Hierarchy

Subway Network

A subway network is composed of all the lines operating in the network. Using parallel-series network modeling technique, it can be concluded that lines in a network operate in parallel. Hence, the network only fails when all the lines operating in the network fail. This can be computed using equation (3.8) and concluded from Figure 3.5.

$$P_{Net} = \prod_{i=1}^{n} P_{Linei} \tag{3.8}$$

Where; P_{Net} = Probability of network failure, P_{Linei}= Probability of line failure, i=1, 2 … n =number of lines per network.

The probability of failure sub-model steps can be summarized as follows;

1. Compute reliability values per elements at lowest level of hierarchy using reliability-based Super model updated to the year 2014 and any recent interventions, if available,
2. Convert the reliability values to Probability of failure for the components at the lowest level of the network hierarchy,
3. Using parallel-series network modeling techniques,
   i. Calculate Probability of failure for the different stations, tunnels, and auxiliary structures of the subway network,
   ii. Calculate Probability of failure of the different lines of the subway network,
   iii. The Probability of failure for the complete subway structural network is developed.

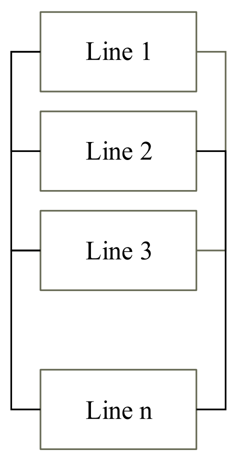


Figure 3.5 A Schematic Diagram for Lines Operating in a Subway Network

3.4 CONSEQUENCE OF FAILURE SUB-MODEL

The second term in a classical risk equation is the consequence of failure. This is the second sub-model to be developed in this research. Figure 3.6 illustrates the steps followed to develop a consequence of failure model. Determining consequence of failure presents a challenging problem to researchers and industry experts due to the uncertainties associated with the different financial, social, and operational impacts. While direct financial impacts of a subway failure can be estimated based on historical data, calculating consequence of failure for intangible factors such as social, economic and even indirect cost of failure 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.

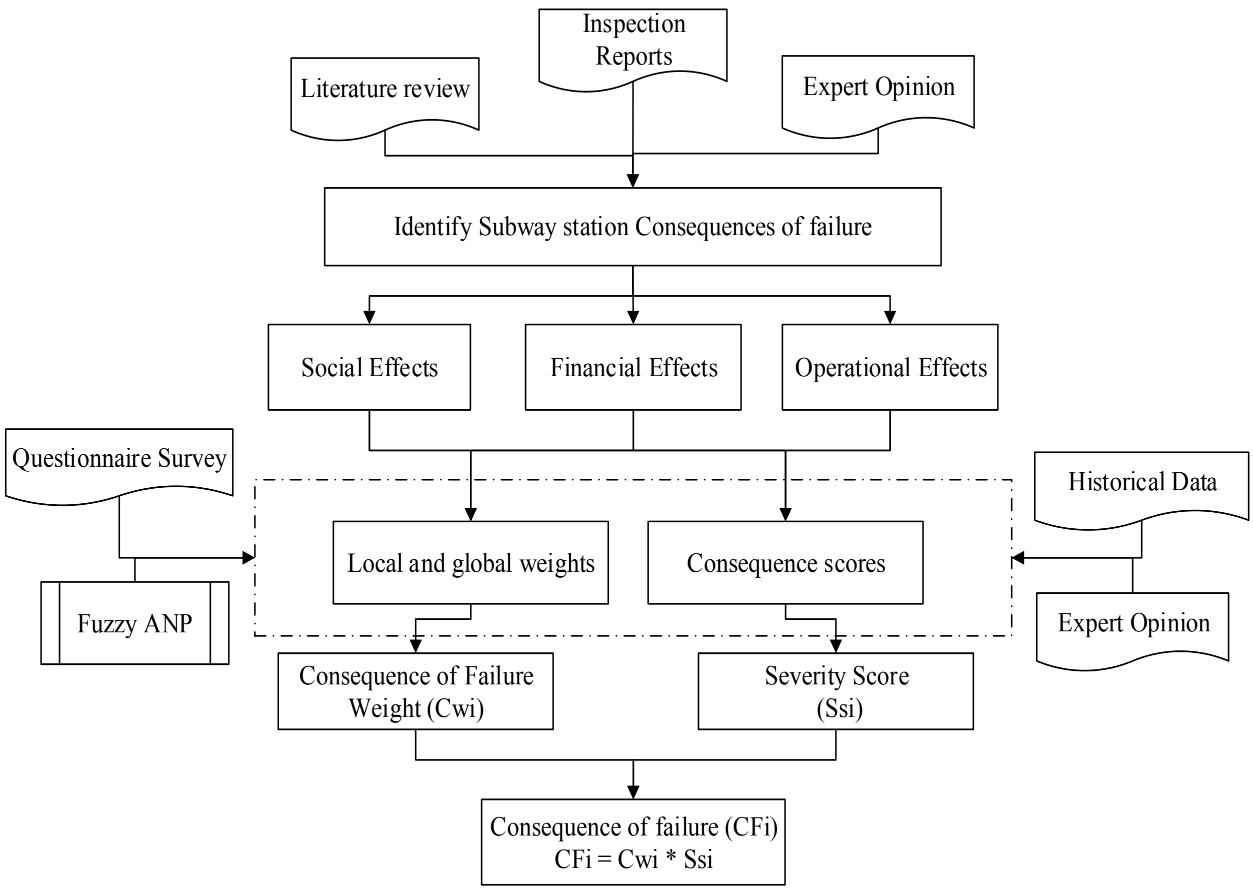


Figure 3.6 Consequence of Failure Model Outline

Indirect impacts of failure in subway stations include, but are not limited to, service disruption, passenger delay, loss of reputation, loss of revenue in addition to other socio-economic impacts. Determining consequences of failure is a highly valuable task since it provides public authorities with a framework for clustering network components based on their relative importance.

Consequences of failure is difficult to estimate due to their intangible multi-attribute nature. The research started by conducting an extensive search to determine the expected consequence of operational failure in a subway network. The main sources of research are the available literature in the subway domain as well as other infrastructure domains in addition to unstructured interview with experts. This research revealed a wide range of expected consequence of failure with high variability. Direct impacts of failure are mainly financial and easy to measure, such as rehabilitation/replacement cost of failed element or revenue loss. Whereas, indirect impacts of failure are more intangible in nature and thus difficult to measure.

The triple bottom line approach is used to determine consequences of failure on a multi-perspective level. This revealed a wide spectrum of consequences occurring at element and station levels. A station is composed of a number of elements operating simultaneously. Based on the location of the element and its nature, the element failure might cause total, partial, or no station closure. This suggests consequences of failure are element-dependent, hence, the consequence of failure sub-model is developed on elements level and aggregated upwards to the stations and network levels of a subway hierarchy using the parallel-series network modeling approach. Based on literature review and expert knowledge, consequences of failure can be broadly grouped into financial, social, and, operational impacts of failure. It is noted that some factors could follow two different perspectives simultaneously. Figure 3.7 demonstrates the main criteria and attributes considered in the consequence of failure sub-model.

Financial Impacts

Financial impacts of failure represent the direct tangible impacts of failure measured in terms of cost of maintenance, repair, or, replacement of the failed component(s). In addition to the expected revenue loss due to partial or total station failure or service interruption, assessed in the operational impacts of failure. User traffic frequency, measured in social impacts of failure, is also a factor of revenue loss. Revenue loss is calculated using equation (3.9);

$$RL = T_f * Fr * TTR/365 \quad (3.9)$$

Where;

RL= Revenue Loss, T_f = User traffic frequency, Fr= Commute Traffic fare, and, TTR= Time to repair (indays)

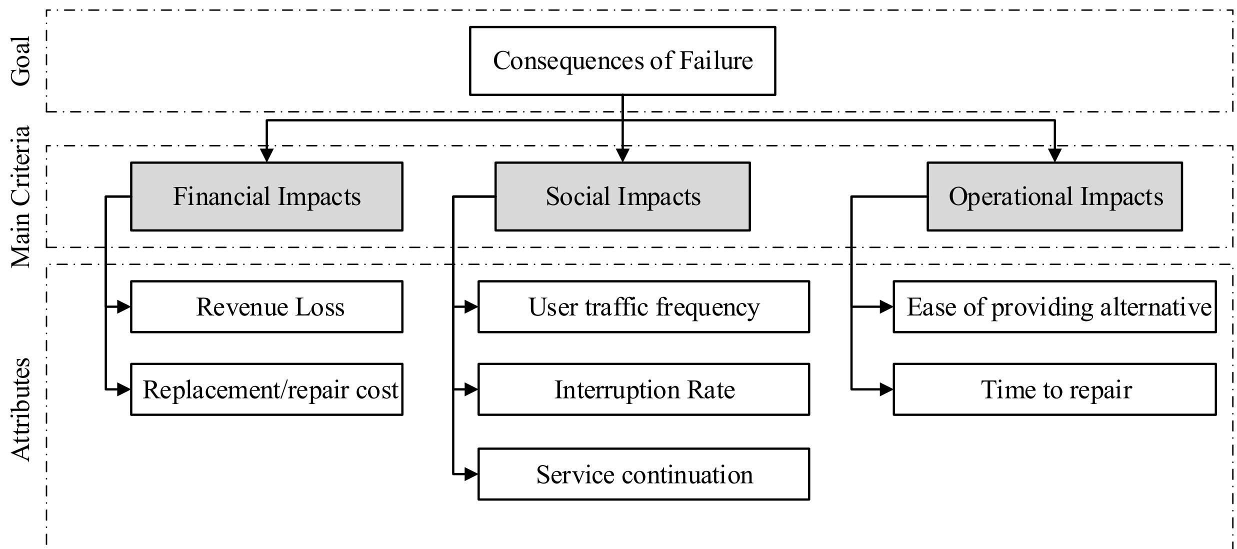


Figure 3.7 Consequence of Failure Attributes

Operational impacts

Operational impacts of failure are those 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. Ease of providing alternative is also a major concern since providing an alternative quickly and easily minimizes the impact of failure and the social costs incurred from this failure. Ease of providing alternative is mainly a factor of the available shuttle buses in case of a station failure. Therefore, it is measured in terms of number of bus stops adjacent to the failed station (in case an alternative is required)

Social impacts

Social impacts of failure are the direct social consequence of failure incurred by the customers. They are measured in terms of the user traffic frequency, interruption rate, and service continuation. 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 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 service continuation refers to whether this interruption will cause total station closure, partial closure, or can be repaired without station closure and service interruption.

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 we only consider operational failure in which serious injury or death is not expected, in which case, the station will be fully closed since the human life is the most valuable and cannot be compared with any consequence.

Examining consequence of failure revealed a level of interdependency between attributes and sub-attributes. None of the specified attributes can be considered independent; hence, cause and effect loops flow between them. This is the type of interdependency precisely modeled by the analytic network process (ANP). Furthermore, these attributes convey a degree of fuzziness and subjectivity derived from using experts' opinion, thus, the Fuzzy Analytic Network Process (FANP) will be utilized to develop the model. FANP addresses the interdependency inherent in the relation between these factors, in addition, it accounts for the uncertainty caused by the use of expert opinions due to the topic subjectivity. In order to determine the overall consequence of failure for each station the following steps are adopted:

- From literature review, inspection reports and experts feedback identify consequence of failure of different elements,
- Categorize consequence of failure according to their Social, Operational, and Financial Impacts,
- Using pairwise comparison and FANP, estimate Consequence of failure Weights(CW_i) .
- Using expert feedback, station configuration and historical data, compute the Severity Scores (Ss_i) ,
- Compute total Consequence of Failure score (CF_i) per element using equation (3.10),

  $$\mathrm{CF_i} = \mathrm{CW_i} * \mathrm{Ss_i} \tag{3.10}$$

- Using system configuration, aggregate consequence of failure for different elements per station, whenever required.

Consequence of failure considered in this research are quite diverse, to overcome the difficulty inherent in these calculations, consequence of failure are measured through indices. This facilitates comparison between expected consequences and highlights areas of higher impact of failure. As discussed in the literature review, FANP will be used as the main analysis tool to obtain the consequence of failure criteria weights. The membership function maps crisp inputs in the universe of discourse (an interval that contains all the possible input values) to degrees of membership within a certain interval, which is usually [0, 1]. Then, the degree of membership specifies the extent to which a given element belongs to a set or is related to a concept. A fuzzy extension of the 5-point fundamental scale proposed by Saaty will be used in the pairwise comparison process. Triangular fuzzy numbers were selected for their wide applicability and ease of comprehension by decision makers. A fuzzy scale of $\tilde{1}$ to $\tilde{9}$ will be used to represent subjective pairwise comparison of the selection process (equal to extremely high) in order to capture the vagueness of the comparison. The scale and its reciprocal are shown in Table 3.1.

Table 3.1 Linguistic Scale of Relative Importance

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

Following the FANP calculation scheme, the consequence of failure estimation sub-model is structured as a network of clusters and nodes. The objective is to determine the relative weight for the different impacts of failure through considering what affects consequence of failure in a subway station and introduce them as clusters, nodes and influence links in a network. The clusters include financial, operational, and social impacts of failure.

The financial impacts cluster includes nodes for maintenance and rehabilitation cost and revenue loss. The operational impacts cluster includes nodes for time to repair and ease of providing alternative. The social impacts of failure cluster include nodes to user traffic frequency, degree of service continuation (whether total /partial/ none) and interruption rate. Once all the nodes are created, one starts by picking a node and linking it to the other nodes in the model that influence it. This is represented by the arrow appearing between the parent node cluster and its children nodes clusters. An arrow is transformed to a loop to the same cluster when a node is linked to nodes in its own cluster; in which case an inner dependence occur.

The linked nodes in a given cluster are pairwise compared for their influence on the node they are linked from to determine the priority of their influence on the parent node. Comparisons are conducted to measure the extent to which a node is more important in capturing “consequence of failure”. These priorities are then entered in the supermatrix for the network. The clusters are also pairwise compared to establish their importance with respect to each other. The resulting matrix of numbers is used to weight the corresponding blocks of the original unweighted supermatrix to obtain the weighted supermatrix and consequently the limit matrix. Consequences of failure are measured on a relative scale against predetermined attributes to capture the multi-perspective impacts of failure. The factors’ weight as well as the stations’ evaluation in terms of these impacts was done qualitatively in light of expert opinion. In addition, the factors selected and their credibility was refined by checking with experts and improving the selected impacts accordingly.

3.5 STATION CRITICALITY SUB-MODEL

When assessing a subway network, other factors exist which should be considered when ranking stations but cannot be counted towards consequence of failure. An example is the number of lines connected in a station. While this factor is important and affects a station ranking, and hence, its risk level, it cannot be included as an impact of failure. On one hand, the number of connected lines cannot be counted as a failure impact that affects consequence of failure; this is because lines are connected on different floors. Hence, the failure of a component on one floor should not affect other floors. On the other hand, if the failed component is by some means affecting the two floors, this should be counted against the failure impacts measurements. The component location was studied and considered in the probability of failure estimation through utilizing the parallel-series network modeling technique to compute the probability of failure values for components and stations. Thus, the location of the component is addressed in a proper manner, however, the state of the station, being a connecting station or not, should still be addressed as a factor affecting the risk of failure of a station. Stations with similar consequence of failure may still show different criticality levels with respect to the station size, location, and intensity of passengers, number of floors, and number of lines passing through the same station. Therefore, the criticality index will be introduced to account for the factors affecting ranking stations for rehabilitations, which cannot be counted towards consequences of failure.

The concept of criticality is introduced in this research as the criticality index. The subway breakdown hierarchy illustrated in Figure 3.2 is utilized for the criticality model development. However, the model calculations are not performed on the elements level like the two previous sub-models. Each level of the breakdown structure was studied to select the most suitable component for using in the criticality sub-model implementation. The component is selected such that its criticality level would be dominant and diverse enough to prevail over the remaining network elements. Consequently, subway stations are selected to be the focus of the criticality analysis. Systems and subsystems share the same major important role of delivering the service; however, their criticality is derived from their respective locations in stations that vary in criticality according to factors and attributes that will be identified later. 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 the systems and subsystems acquire the same criticality level as the stations in which they operate. Equally, a line criticality is computed as the weighted summation of criticality indices for the total number 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.

The station criticality is a complex decision based on different attributes such as number of lines and levels in a station, station use whether end or intermodal, and station location in proximity to all types of attractions. The criticality model framework is outlined in Figure 3.8 based upon literature review, experts' opinion and by consulting several subway networks. Criticality of a subway station is identified by three min attributes and seven sub-attributes. Main criticality attributes are station characteristics, station location, and, station nature of use. Attributes and sub-attributes of a criticality index are illustrated in Figure 3.9.

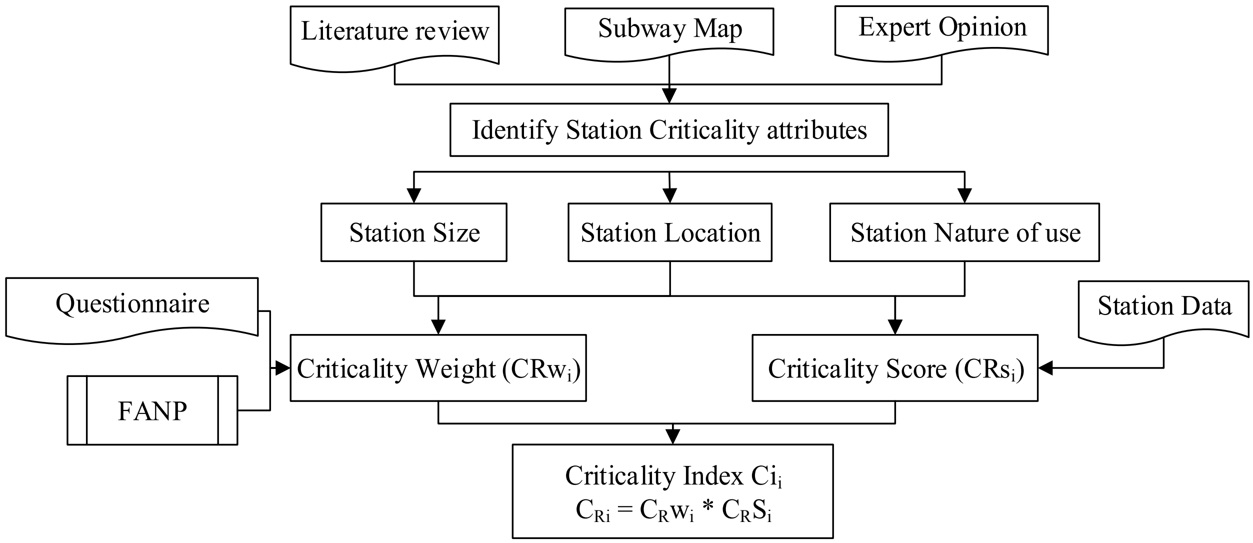


Figure 3.8 Criticality Sub-model Framework

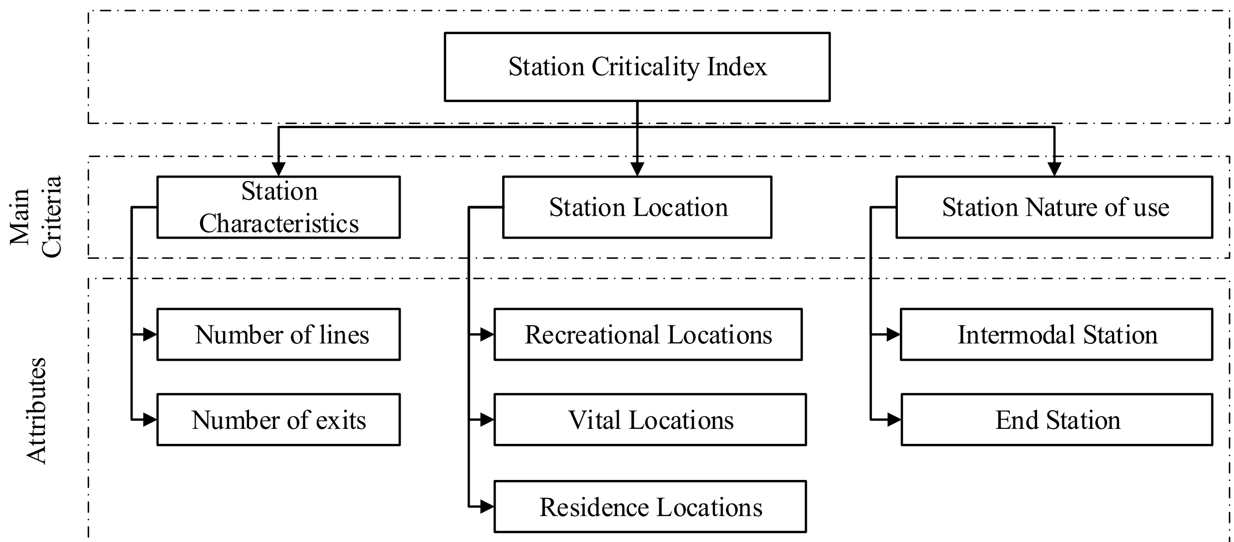


Figure 3.9 Criticality Sub-model Attributes

Station characteristics

Number of lines: the larger the number of lines connected at the same station the larger the passenger frequency and consequently the station criticality. Based on the maximum number of lines as defined by user for the network under study, the score for number of lines is computed as the normalized value per attribute.

Number of exits: The importance of a station is directly proportional to the number of exits per station, they reflect the designed passenger capacity and the expected importance of the station.

Station Location

Some stations have larger criticality due to their proximity to important location where the service is more required and the frequency of passengers is higher (ex. hospitals, recreational areas, universities …). Based on the data collected from experts, the score of each station with respect to its location will be calculated. Relative importance of the different locations will be obtained from experts and the score will be measured accordingly. Locations clustering are obtained by examining current network map and through consulting numerous field experts. Accordingly, a station is identified in terms of its location being in proximity to recreational, vital, or, residence locations. A binary value is assigned per station per location, in addition, a combined location option is permitted, and hence, a station can have value in all location attributes.

Station Nature of Use

End station; end stations pose a greater importance and consequently criticality since the intensity of passengers at an end station is expected to be higher. The score for this attribute will be computed as a binary value. If a station is an end station it will take a value of 1, if otherwise, then a value of 0 will be assigned.

Intermodal station: Intermodal stations pose a greater importance and consequently criticality since the intensity of passengers at these stations is expected to be higher than normal stations. The score for this attribute will be computed as a binary value as well. A station acquires a score of (1) if it is an intermodal station and 0 if otherwise.

The attributes and sub-attributes considered in the criticality index model are summarized in Table 3.2. The attribute scores are computed based upon the network under examination and individual station information. The scores are obtained as shown in Table 3.3

Table 3.2 Subway Systems Criticality Attributes

Factor	Attributes	Description
Station Size	Number of lines	Station size reflected as number of lines and number of exits composing the station
	Number of exits	
Station Location	Recreational	Station criticality based on its proximity to important locations where higher passenger frequency is expected
	Vitalities	
	Residence	
Station Nature of Use	Intermodal Station	Station criticality derived from its nature as an intermodal station
	End station	Station criticality derived from its nature as an end station

From the definition of criticality attributes, inner and outer dependency occur between attributes analogous to those in the consequence of failure model. Consequently, FANP was selected to assess criticality attributes, and a weight component is introduced in the criticality index equation to accommodate the subjective variability in the attributes weight. The score of each attribute is factor-dependent; it can be seen as a scale from less to more critical.

The criticality index model is summarized in the following steps;

- Identify criticality attributes using literature review and experts opinions,
- Estimate criticality attributes weights (C_RW_i) using pairwise comparison and FANP with application to FPP,
- Perform FPP on each comparison matrix individually to derive sets of local priorities,

Table 3.3 Criticality Attributes Definition and Scores

Factors	Attribute	Definition	Score
Station Size	#exits	The increased number of exits reflects an increase in expected passenger capacity	Based on the maximum number of exits as defined by user for the network under study
	# lines	The increased number of lines reflects an increase in expected passenger capacity	Based on the maximum number of lines as defined by user 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) in case station is an intermodal station and (0) if else
	End station	End stations pose a greater importance since a higher passenger frequency is expected.	Computed as binary value, (1) in case station is 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 binary value, (1) in case station is located in a high capacity location and, (0) if else

- Calculate the weights using the FPP method according to equation (3.11). 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,

Max λ (3.11)

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} Lower, medium, and, upper bounds of triangular judgments respectively.

- Using expert opinion, station configuration and historical data, compute criticality scores ($C_R Si$) ,
- Compute the total Criticality Index per station (C_R) using equation (3.12),

$$C_R = \sum_{i=1}^{n} C_R W_i * C_R S_i \quad (3.12)$$

Among the selected attributes contributing to an increased station criticality, the station location is the most diverse. The Montréal subway network is used as a major case study to further develop the model as explained in the model implementation section.

3.6 THE RISK MODEL

Classical Risk Equation (Multiplication)

Risk by definition is the combination of probability and severity of adverse effects an infrastructure encounters. In which case, the risk can be expressed by equation (3.13)

Risk = Probability of failure * Consequence of failure (3.13)

This equation is a direct and straightforward computation of the risk value. It provides an illustration of the risk level over the entire network. The multiplication method is very useful especially if consequences of failure can be expressed in monetary terms. In which case, the risk value will convey the expected loss from the event occurring. Apart from its simplicity, this method cannot be applied for the subway networks for several reasons. First, it requires that the probability and severity be expressed in numerical values. Due to the data scarcity problem faced in this research, this method was regarded infeasible for subway networks. Second, the high level of uncertainty and intangible factors associated with the consequence of failure of subway elements yield this method inaccurate. Third and last, this method does not have the ability to distinguish between the case of high probability of failure with low consequence of failure and the case of low probability of failure with high consequence of failure. Using direct multiplication yields the same risk value in both cases although the counteraction adopted by the authorities in each case will be entirely different.

The Risk Matrix

Risk matrices measure probability of failure and consequence of failure on an ordinal scale. The risk matrix is then constructed by combining probability and consequence of failure on a matrix to assign different risk levels. This method overcomes the main drawback of the multiplication method through creating a visible risk matrix. This facilitates distinguishing between cases of high probability of failure with low consequence of failure and low probability of failure with high consequence of failure. Risk matrices were used by sewer agencies to combine condition assessment scores and consequence of failure indices to obtain a risk of failure value (Baris 2010). Table 3.4 shows a sample risk matrix where the difference between the two extreme cases can be easily spotted.

Risk matrices can easily differentiate between the two extremes of high probability and low consequence of failure and low probability with high consequence of failure through the visual representation. However, risk matrices depend on categorization of probability and consequence of failure into ordinal scales, which cause the loss of a significant amount of information because of the recoding. In addition, the cut-off values selected to transfer probability and consequence into ordinal values might not be the same for all cases. Especially in cases when the probability is originally provided in a subjective manner like “very high” and “very low”. Another problem appears at the boundaries of the ordinal scale where values might be in close proximity to each other but fall into different categories.

Table 3.4 A Sample Risk Matrix

	Consequence of Failure				
Probability of failure	1 (very low)	2 (low)	3 (medium)	4 (high)	5 (very high)
1 (very low)	very low	very low	low	medium	medium
2 (low)	very low	low	medium	medium	medium
3 (medium)	low	medium	medium	medium	high
4 (high)	medium	medium	medium	high	very high
5 (very high)	medium	medium	high	very high	very high

The Fuzzy Rule Based Technique (FRB)

The Fuzzy Rule based technique derived from fuzzy logic permits users to integrate their experience into the decision support system through using “if-then” rules. Fuzzy sets allow for a more precise presentation of element’s membership particularly when it is difficult to determine the boundary of the set as crisp values. The Fuzzy Rule based model consists of a set of if-then rules defined over fuzzy sets. The rules are usually created using “expert knowledge”. The relationship between different fuzzy variables is represented by if-then rules of the form “If antecedent…… Then Consequent”.

The output of any risk equation is a risk index that represents the risk level of each system while considering intangible consequence of failure. When studying the risk level, it should be noted that elements with similar probability of failure might show wide variation in terms of consequence of failure and vice versa. In addition, critical elements with high consequence of failure usually compose a smaller portion of the overall network. Accordingly, focusing only on these elements would result in an unbalanced management practices since unexpected failures may occur in less-critical elements, which constitute the majority of the network. On the other hand, focusing only on elements with high probability of failure result in a biased management strategy since the failure of an element of high consequence of failure may overcome any gains obtained from the proactive management of the less critical elements of the network.

In addition, a comprehensive risk assessment should consider the relative importance of different components and systems of a subway network. A criticality index is introduced to measure the relative importance and consider it in the risk index development. Consequently, a new term is added to the risk equation, which is named as the criticality index (C_R).The proposed risk equation is shown Equation (3.14).

Risk = Probability of failure * Consequence of failure* Criticality Index (3.14)

The literature review demonstrates the different methods used to compute the risk value along with their advantages and disadvantages. The fuzzy inference engine will be used to combine the components of a risk equation and conclude the resultant risk index for different combinations. The output of the three sub-models developed earlier, the Probability of Failure, Consequence of Failure, and, Criticality Model, yield the basic inputs required for the fuzzy risk equation. The fuzzy risk index model is illustrated in Figure 3.10. The risk equation is formulated using Mamdani algorithm as presented in equation (3.15)

RI: IF PoF is Xi and CoF is Yi and C_R is Zi then Risk is Li (3.15)

Where, i= 1, 2, 3 ….k, Xi. Yi, Zi, and Li are linguistic constants as defined in model, k = number of rules.

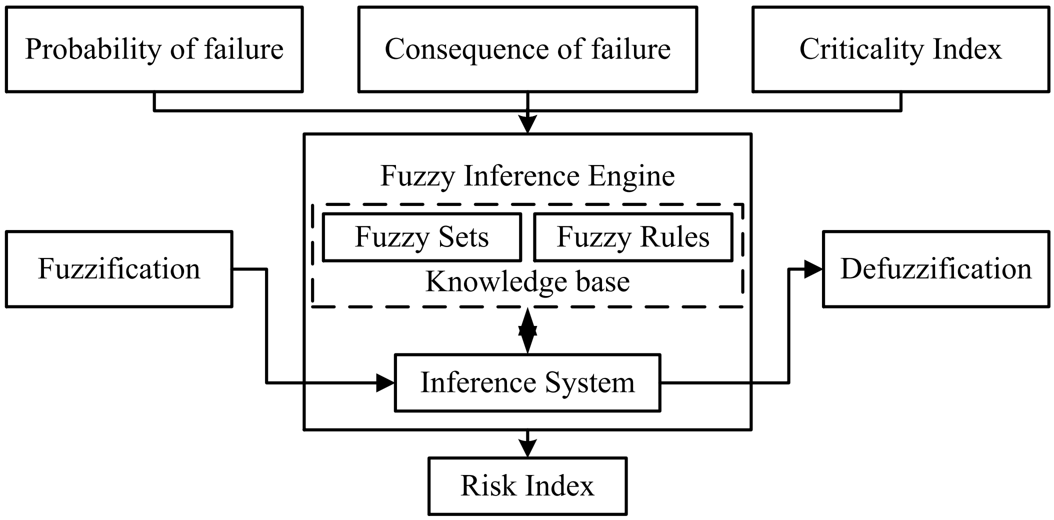


Figure 3.10 The Fuzzy Risk Index Model

The following assumptions are considered in the risk index computations;

- The (PoFi) is measured per element at the lowest level of the network hierarchy, with flexibility of aggregating into higher levels.
- The (CoFi) is measured per elements at the lowest level of the hierarchy with possibility of aggregating to higher levels.
    - For tunnel and auxiliary structures, the consequence of failure will be assumed as the higher value from the corresponding stations.
- The Criticality Index (C_R) is measured per station,
    - Criticality of lower levels of hierarchy are the same as the station in which they operate,

- For tunnels, CR is the higher of the two connected stations.
- For auxiliary structures, CR is the same as the corresponding station.

The risk index model entails four main steps explained as follows,

Fuzzification

Crisp values are transformed into linguistic terms using grades of membership functions assigned to each input value. Different methods are available for predicting membership functions, in our case; experts are consulted to construct membership functions representing each one from the three sub-models and map it to linguistic terms of fuzzy sets. Triangular membership functions are used due to their wide applicability, flexibility, and ease of comprehension by experts.

Knowledge base

The knowledge base incorporates the human expert in the model to develop the relation between the antecedents and the consequents in the "if then" rules. Human expertise translated through knowledge base is used to map the relation between the model input and output variables. This research had three main sources of knowledge acquisition, reports, literature review, and unstructured questionnaires.

Fuzzy inference system

The fuzzy inference system uses the rules derived in the knowledge base and membership functions developed for input and output variables to aggregate rules and conclude model. The Mamdani model, known for its simplicity, is used in this research to model the algorithm.

Defuzzification

In this step, fuzzy sets are transferred into crisp values using the centroid of area method and equation (2.21). As stated in the literature review, the COA method has the advantage that all activated membership functions of the conclusions (all active rules) take part in the defuzzification process. The risk index is calculated on elements level. Using the network modeling approach, risk index values can be computed for all other levels of the hierarchy such that a system in series fails upon the failure of one of its components, whereas a system in parallel fails when all its components fail. The equations for aggregating risk index are seen in equation (3.16) for systems in parallel and equation (3.17) for systems in series.

$$R_{\text{system, series}} = 1 - \prod_{i=1}^{n} R_i \tag{3.16}$$

$$R_{\text{system parallel}} = \prod_{i=1}^{n} R_i \tag{3.17}$$

Where, R_i= risk index for the elements at a designated level of the network hierarchy, i=number of elements per level= 1, 2…n

3.7 THE BUDGET ALLOCATION MODEL

Subway systems are complex structural systems that deteriorate with time due to wear, fatigue, multiple aggressive environmental factors, inadequate maintenance and inspection, or, poor workmanship and design. However, high costs associated with Maintenance and Rehabilitation (M&R) requires a robust prioritization scheme for the optimum allocation of budget across the network while maximizing the performance. Budget allocation is a versatile problem where the solution set is limited for each component but large for the whole system. Its combinatorial nature makes obtaining an exact solution a difficult task. Genetic Algorithms (GA) was successfully used in solving optimization problems of that nature, where optimum or near-optimum solutions are a combination of the components' solutions. Consequently, it was selected to develop the risk based budget allocation model presented in this section.

The budget allocation problem in our case is a mixed one in which the risk calculations are done on different levels to calculate the network risk index. On the other hand, the budget calculations will follow a different technique. The budget is allocated along network level while considering the component level calculations and requirements. This approach enables an improved evaluation of the effectiveness of maintenance strategies and determines the optimal solution to achieve the best trade-off between all criteria, including conflicting ones, such as cost and risk. This model aims to optimize the infrastructure risk index while allocating budget to the several competing components of the network. The network-level methodology is a very rational solution because its ultimate objective is to improve performance of the entire subway network instead of merely that of individual structures in the network.

The goal is to obtain a series of maintenance actions applied over a specific time horizon (a year) that, in an optimized tradeoff manner (1) minimize the largest risk indices, (2) minimize the overall risk index, and (3) minimize the total cost spent over a specified time horizon. The conditions are enforced such that the risk index should always be under a threshold specified by the decision maker. The threshold of the risk index is mainly adopted form the threshold of the probability of failure and the consequence of failure. Criticality values cannot be used to enforce a threshold value on the risk index since they convey in different means the importance of the station and its optimized priority for rehabilitation.

The model aims at accurate and appropriate distribution of the available budget among competing network components, while maximizing the efficiency of the spent money.

Consequently, the model allocates the limited budget across the network based on the risk index calculated per component. The model framework is illustrated in Figure 3.11.

The objective function is defined as the components of the risk index equation. The decision variables are the rehabilitation actions including the cost of rehabilitation action, percentage (%) improved, and, time to repair. The main constraints imposed are the total available budget per calculation period (year) and the threshold for the risk index. The objective of this model is to maximize the gained benefits from the available budget using equation (3.18) and equation (3.19).

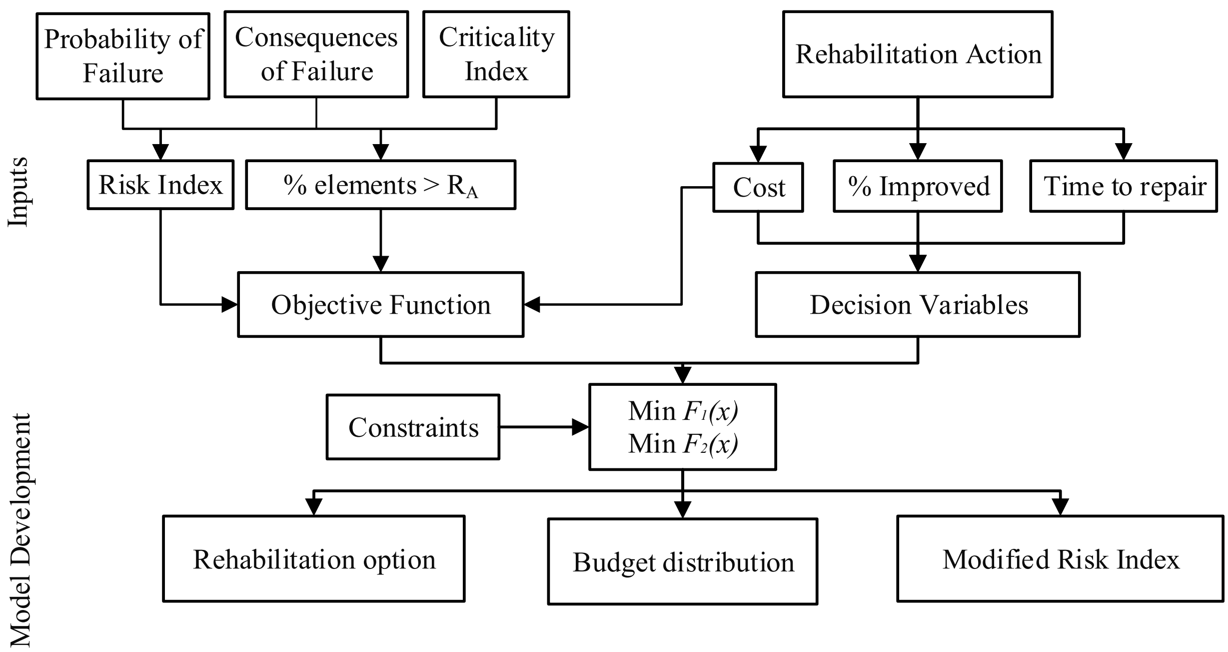


Figure 3.11 The Budget Allocation Model

The optimization objectives are;

$$Min\ f(x) = RI * w_1 + RI_A * w_2 \tag{3.18}$$

$$Min \sum_{i=1}^{n} \sum_{j=1}^{k} C_{ij} \tag{3.19}$$

Subject to the following constraint;

$$\sum_{i=1}^{n} \sum_{j=1}^{k} C_{ij} \leq C_{max} \tag{3.20}$$

Where;

RI= Integrated risk index,

RI_A=Percentage of elements with a risk index equal to or exceeding the risk appetite set by decision maker,

A = Risk threshold as set by decision maker,

w= weight of optimized objectives, such that$\sum_{i=1}^{2} w_i = 1$,

C_{ij}= Cost of rehabilitation strategy j applied to element i,

C_{max}= Total available budget for the infrastructure per year,

$C_{ij} \leq C_{max} \neq 0$

i= Elements at lowest level in subway hierarchy = 1, 2, 3…n

j= Selected rehabilitation strategy = 1, 2, 3…k, k=5

n= Number of elements /infrastructure,

This is a priori model; the weights of the optimized objectives are set and provided by the decision maker. Inputs include:

1. Number of components composing the station system
2. Probability of failure per component
3. Consequence of failure per component per station

4. Criticality index per station
5. Asset rehabilitation strategy and the associated cost and expected level of improvement.

The expected solution space of this problem is large due to the diversity of components and rehabilitation actions options per components. In addition, near-optimal solutions are acceptable in these types of problems especially when the analysis is conducted on a network level. The model builds on the risk index computed earlier. As explained, the risk index is a qualitative measure of the subway infrastructure integrity and reliability.

The extent of Maintenance and Rehabilitation (M&R) actions differ greatly depending upon the state of component under assessment. The action taken could be the simplest and cheapest like preventive maintenance or the case might require the other extreme of element replacement, which would be the most expensive and complicated option. Network level assessment requires the action be selected on a higher level than the component level. Accordingly, five generic M&R treatment levels are assumed. Each treatment action is associated by an expected level of improvement, expected cost in $\$/m^2$, and, expected time in days to be efficiently accomplished. Optimization using Genetic Algorithms (GA) implies the following steps:

1) Generate a random feasible population of solutions (chromosomes)

2) Evaluate each chromosome's fitness and arrange them accordingly

3) Perform Elitism by copying the highest fitness chromosome to the new population (To keep best solutions unharmed in the reproduction phase)

4) Select two chromosomes from the current population based on their fitness

5) Perform Crossover and Mutation resulting in a new solution

6) Repeat the previous step until the new generation is produced

7) Evaluate the new population and check if the stopping criteria are satisfied or not.

Population Initialization

Population size is the number of chromosomes per each generation. No specific rules exist for determining the population size; however, according to (Goldberg and Holland, 1988) a higher number of chromosomes reflect a higher probability to achieve rapid convergence. The rule of thumb is that a population of 50 to 200 is suggested.

Chromosome Encoding

The chromosome encoding is done as an array of genes. Each "stations system" is represented by 12 genes representing the last level in the hierarchy in need for rehabilitation. The total number of cells in each chromosome equals to 12 multiplied by the number of station systems to be assessed. The encoding for each gene indicates the M&R action number applied for that element.

Figure 3.12 illustrates the proposed encoding structure for the optimization problem.

Fitness Calculation

Once the population is created, each chromosome is assigned a fitness value based upon its characteristics and binding to the objective function. The individuals with higher fitness value have a higher probability of being selected as candidates for further examination. The fitness function is usually considered the same as the objective function in case of maximization problems. In our case of a minimization problem, the inverse of the objective function is used as the fitness function.

$$\text{Fitness}=\frac{1}{\sum_{z=1}^{Z} RI_z} + \frac{1}{\sum_{i=1}^{n}\sum_{j=1}^{k} C_{ij}} \qquad (3.21)$$

In case of a chromosome that violates the budget constraints, the fitness of the chromosome will be decreased using a new fitness function. This is done to preserve the chromosome for further computations, since violating the budget does not mean that the entire chromosome is bad, on the contrary, it might bear some good genes.

$$\text{Fitness'} = \frac{1}{\sum_{z=1}^{Z} RI_z} + \frac{1}{\sum_{i=1}^{n}\sum_{j=1}^{k} C_{ij}}\left(1 - \frac{C_{ij}-C_{\max}}{C_{ij}}\right) \tag{3.22}$$

Where;

Cij =The chromosome budget, C_{max}= Maximum available budget

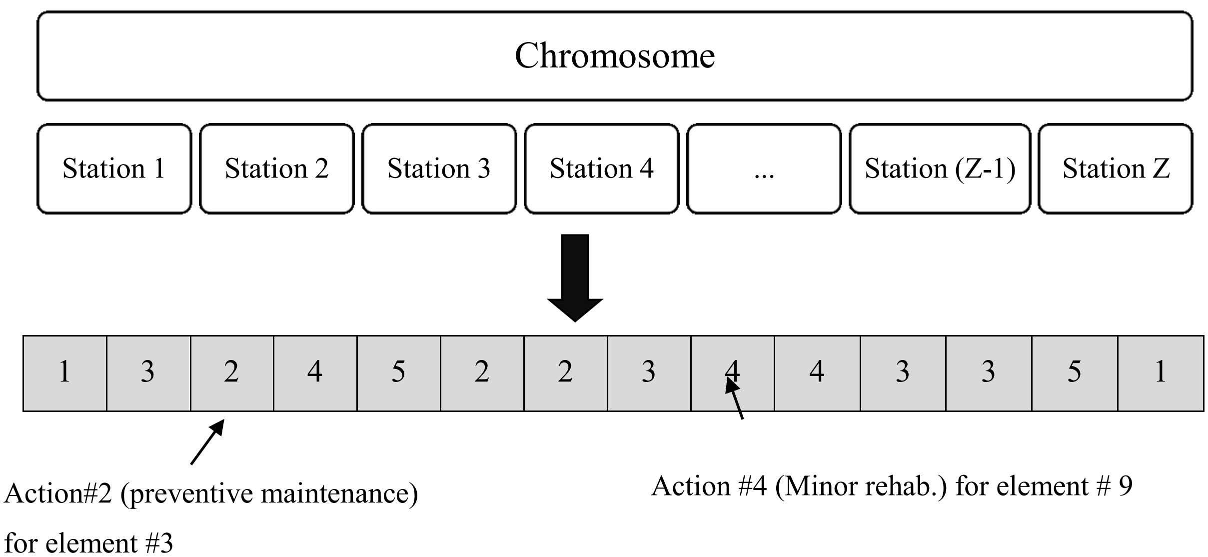


Figure 3.12 Proposed Chromosome Encoding

Executing Genetic Algorithms

For the first round of chromosomes, the do nothing action is selected for all the elements, this provides a basic look on the expected risk index on element and network levels. A set of feasible actions is determined for each element and, based on these actions, a random population is created. The first generation is usually done randomly. However, according to (AL-Battaineh 2007) the generation of first population is designed with the following percentages: 1) 70% "Do

Nothing"; 2) 20% "lowest spending action"; and 3) 10% randomly generated. This distribution is the most appropriate for cases of limited budget since it generates chromosomes with lower total costs, which is a feasible solution. Later GA actions evolve those chromosomes and glide them to higher levels. This modification has been tested and showed the ability of finding a good solution in a shorter time (AL-Battaineh 2007).

Crossover and Mutation

Crossover is performed by selecting two parents from the current population. One-point or two-point crossover is performed through selecting a random point(s) along the chromosome length and swapping the corresponding points of the parents' chromosomes to get the off springs. Mutation is then performed through replacing the gene in a chromosome with a random number (representing the rehabilitation strategy) to produce a new chromosome. The new chromosome is then checked against the optimization constraints, if it is not applicable, a new random number is used.

Stopping Criteria

The optimization will stop if any of the stopping criteria are reached, interrupted by user, or, if the maximum number of generations defined, is reached. The main output of this system is the infrastructure risk index evaluated on the assigned actions for each element. Three major outputs are expected (1) budget distribution, (2) proposed rehabilitation actions across the components, (3) current infrastructure risk index, (4) expected infrastructure risk index at the end of the planning year, (5) available budget, (6) used budget, (7) unused portion of the budget if any. This model allocates budget for subways infrastructure systems utilizing genetic algorithms by optimizing a systems Risk Index. The optimization objective is to minimize the system risk index by finding the optimum allocation of the available budget.

3.8 SUMMARY

This chapter illustrates the proposed methodology for developing a risk-based budget allocation model. The framework is composed of three sub-models and two main model. Reliability based Weibull curves are used to deduct probability of failure per elements adjusted to year of construction, current year and year of inspection. Consequence of failure model used FANP to calculate local and global weights of the failure attributes identified. Likewise, the criticality index uses FANP to calculate local and global weights of different criticality attributes. The fuzzy inference engine is used to develop a fuzzy risk model. The three sub-models act as input in the fuzzy model where the output is the expected risk index per system. The risk index is used to prioritize systems across subway networks for rehabilitation in the risk-based budget allocation model. All sub-models and models calculations incorporated in the framework are done using an automated tool as illustrated in the model implementation section. The data gathering techniques is covered in the following chapter. Different sources of data including survey, literature review, inspection reports and interviews are discussed in depth.

CHAPTER 4. DATA COLLECTION

4.1 INTRODUCTION

The proposed framework development requires data collection at different stages of the methodology. The probability of failure sub-model is developed based on the analysis of a segment of the Montreal subway network. Data sources include inspection reports provided by STM and literature review. The consequence of failure and the criticality models require incorporating expert knowledge and engineering judgment along two stages; attributes selection and weights calculations. The fuzzy rules of the risk index model together with the membership functions are also developed by means of experts' input. Data collection therefore was gathered using inspection reports, structured and unstructured interviews, and a survey.

Structured and unstructured interviews were held with experts from operations and structural department in STM along the various stages of the model development. The main purpose was understanding the problem beforehand and ensuring the developed model represents the real-life problem and incorporates the various conflicting factors. The credibility of the designed survey was also confirmed during interviews after which some modifications were incorporated.

The following section explores the different data collection methods undergone throughout the research. The first section explains in details the case study used for model implementation. The subsequent sections cover the inspection report and the survey launched online and distributed by hand to collect data necessary for the various sub-models and models development.

4.2 CASE STUDY

Montreal subway is one of the oldest in North America constructed in the year 1960. It has 68 stations spreading on a total length of 69.2 kilometers along four lines and covering the north, east, and center of the Island of Montreal with connections to Longueil, and Laval. Semaan (2011) implemented his reliability-based model on a segment of the Montreal subway. Following the generic subway network hierarchy proposed in Figure 3.2 in Chapter 3, the segment contains six station buildings falling on three intersecting lines. All systems were constructed in the year 1966 and fall on two of the oldest lines composing the subway network. This specific segment was selected based on the availability of inspection reports for most of stations falling on it, thus further reinforcing the model. In addition, the segment comprises two of the oldest lines in the network with station (STA 2) being a connecting station for three lines and having the highest ridership across the network.

The selected segment is composed of three lines with two stations falling on Line A (STA1 and STA 3), two stations on Line B (STA 4 and STA 5) and, one station on Line C (STA 6). The interconnecting station between the three lines (STA 2) is also considered in the segment for a total of six subway station buildings. Note that STA 2 falls on the three lines, however, based on the highest ridership values, it is considered a part of Line A. Six station buildings (STB) are considered for calculations accompanied with six Station (STA) systems, six tunnel (TUN) systems, and, six auxiliary (AUX) structure systems. All systems considered will be given symbolic names for confidentiality.

Table 4.1 shows the station buildings under consideration accompanied by the different elements acronym, system name, number of levels per station building, and the line on which the different systems operate. Each station system (STA) is given the name of the station in which it operates. Tunnel systems (TUN) acquire the names of the two stations through which they operate.

Table 4.1 Case Study Segment Identification

Station Building	System Acronym	# Levels	Line
STB 1	STA 1 TUN 1 AUX 1	3	Line A
STB 2	STA 2 TUN 2 AUX 2	3	Line A
STB 3	STA 3 TUN 3 AUX 3	3	Line A
STB 4	STA 4 TUN 4 AUX 4	5	Line B
STB 5	STA 5 TUN 5 AUX 5	4	Line B
STB 6	STA 6 TUN 6 AUX 6	3	Line C

Auxiliary structures systems (AUX) are given individual names based on the plans provided in the STM inspection reports and maps. Most station buildings in the network are composed of three levels, it can be seen that this segment is no different with 4 out of 6 stations having three levels. STA 4 is the lowest in the entire network at 29 meters and thus has 5 levels followed by station STA 5 with 4 levels.

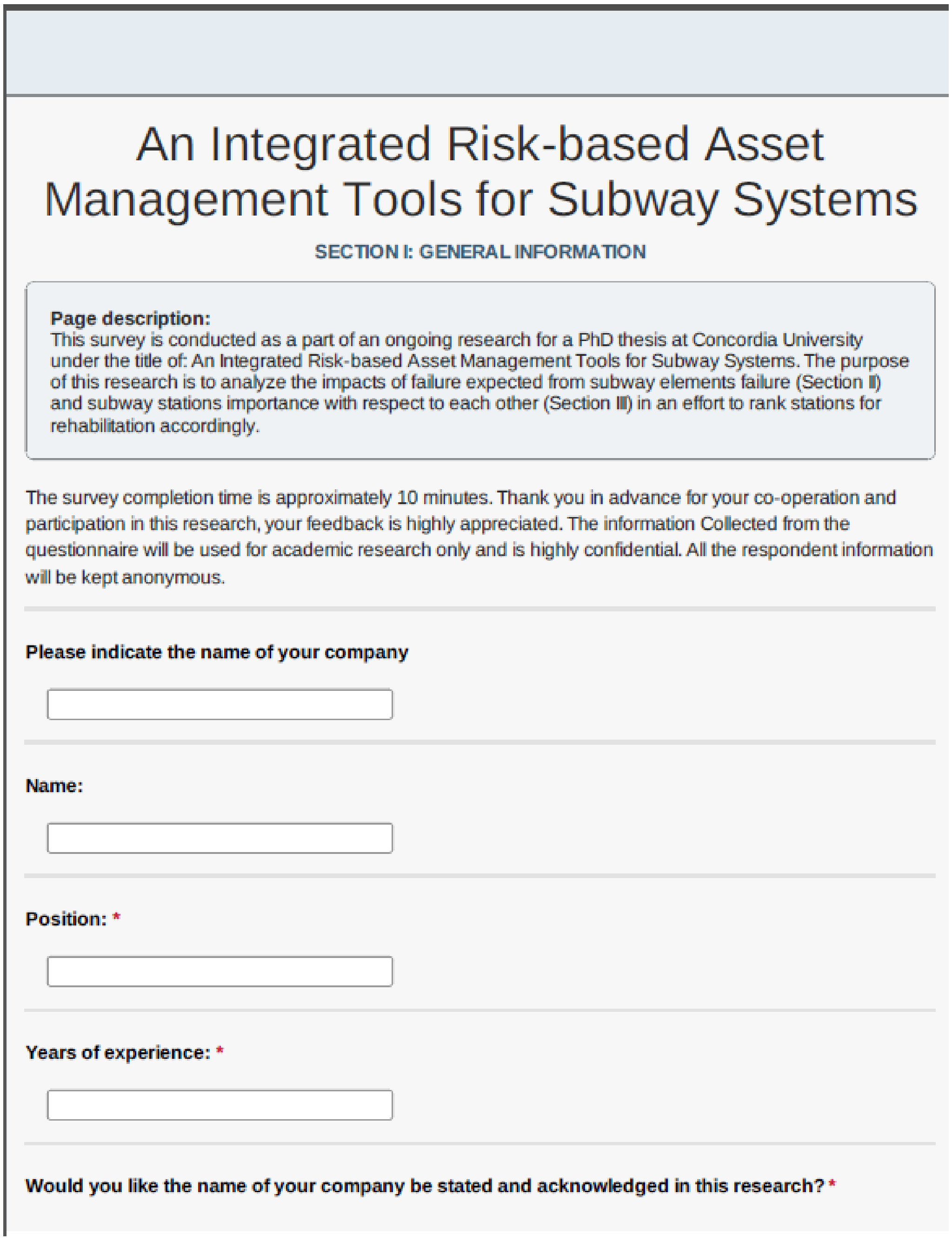
4.3 INSPECTION REPORTS

STM inspection reports contain a wealth of information pertaining to the different systems and elements operating within the network, their history, characteristics and location. Inspection reports were provided by the STM engineering unit operating as the rehabilitation team, whereas the M&R reports were provided by the STM planning unit. It is noted that the inspection history is irregular and very detached. Discrete inspections were done on different station buildings between the years (1992-2005), which is the range of inspection reports provided. No specific inspection scheme can be identified; some stations have up to 3 inspection reports whereas others have none. The "Reno-Station II" program was executed in 2005 and aimed at renovating all stations constructed in the year 1966. Consequently, maintenance and rehabilitation actions performed on elements in 2005 are assumed to improve the overall performance to 90% of total performance. In addition, the remaining service life after the M&R action is assumed 90 years proportional to the revised performance. It was also noted that there was no complete inspection report on the network level for any given year. Nevertheless, the information required for the framework development was extracted from the report including; (1) Station building systems' year of construction, (2) Structural plans, (3) Elements configuration, (4) Station characteristics, (5) Number of floors and exits per station, (6) M&R action performed (if any) and year of action, (7) Range of M&R actions, repair cost, time to repair, and, cost breakdown.

4.4 QUESTIONNAIRE SURVEY

The consequences of failure and criticality models require conducting pairwise comparisons between goals, attributes, and, main criteria while considering the level of interdependency between them. A questionnaire was constructed for that purpose, a sample questionnaire is shown in Appendix A. The questionnaire was built and hosted on an external survey website to facilitate answering the questionnaire and communicate inquiries. Moreover, the questionnaire was available for download in an offline mode and was communicated to experts through personal emails. The questionnaire is composed of three sections. The first section (Section I), shown in Figure 4.1, states the Survey name and purpose. It contains a brief description of the purpose of the survey and its targeted recipients. This section gathers general information about the respondents including name, position (obligatory) and years of experience (obligatory). In addition, answering guidelines are provided to demonstrate how to conduct the comparison process accompanied by a sample filled pairwise comparison matrix. The graph explains the pairwise comparison concept, how it is done, and the significance of the pairwise comparison cell chosen as shown in Figure 4.2.

The second section of the questionnaire (Section II) starts by the consequence of failure model hierarchy and contains the pairwise comparison matrices of the model. Seven pairwise comparison matrices and two open ended questions are provided. The pairwise comparison is conducted on three levels, a) Main criteria comparison with respect to goal, b) Main criteria comparison with respect to each other, and c) sub-criteria comparison with respect to main criteria. Pairwise comparison questions are provided in a matrix form in the hard and email copy. A sample pairwise comparison matrix is shown in Figure 4.3. Pairwise comparison was also offered in a Multiple-Choice Question (MCQ) format in the online and downloadable copy as seen in Figure 4.4. Two open-ended questions are available at the end of the second section for the respondent to suggest any modifications and communicate any concerns.



An Integrated Risk-based Asset Management Tools for Subway Systems

SECTION I: GENERAL INFORMATION

Page description:
This survey is conducted as a part of an ongoing research for a PhD thesis at Concordia University under the title of: An Integrated Risk-based Asset Management Tools for Subway Systems. The purpose of this research is to analyze the impacts of failure expected from subway elements failure (Section II) and subway stations importance with respect to each other (Section III) in an effort to rank stations for rehabilitation accordingly.

The survey completion time is approximately 10 minutes. Thank you in advance for your co-operation and participation in this research, your feedback is highly appreciated. The information Collected from the questionnaire will be used for academic research only and is highly confidential. All the respondent information will be kept anonymous.

Please indicate the name of your company

Name:

Position: *

Years of experience: *

Would you like the name of your company be stated and acknowledged in this research? *

Figure 4.1 A Screenshot from First Page of Questionnaire

This survey estimates the relative importance of the expected consequences of failure and subway stations criticality to be further used for risk assessment. The comparison between factors will be conducted using a pairwise comparison matrix and a scale that expresses the qualitative judgments between criteria numerically. The scale indicates the relative importance through answering the question; "Given a control criterion (Z) which of the two criteria (X) and (Y) is more dominant with respect to (Z) criterion?" Kindly indicate your preference through selecting the number that best represents your point of view. The following table illustrates an example.

Example:

In the table below, consider comparing ***"Social Impacts"*** (Criterion X) with ***"Financial Impacts"*** (Criterion Y) with respect to ***"Consequences of failure"***.

With respect to Z "Consequences of failure"										
Indicate the relative importance of (X) on (Y) or vice versa										
(X)	Absolute	Very Strong	Strong	Moderate	Equal	Moderate	Strong	Very Strong	Absolute	(Y)
Social Impacts	(9)	(7)	(5)	(3)	(1)	(3)	(5)	(7)	(9)	Financial Impacts
	(9)	(7)	(5)	(3)	(1)	(3)	(5)	(7)	(9)	Operational Impacts

*If you consider that "Social Impacts" is more important than "Financial Impacts" and the degree of importance is **"Strong"** then circle the number (5)*

If you consider that "Social Impacts" is equally important to "Financial Impacts" then circle the number (1)

*If you consider that "Financial Impacts" is more important than "Social Impacts" and the degree of importance is **"Absolute"** then circle the number (9)*

*The same procedure is then followed when comparing **"Social Impacts"** with **"Operational Impacts"**.*

Figure 4.2 Explanatory Graph Provided in Questionnaire

A. Main criteria comparison with respect to goal " Consequences of failure" ;

With respect to Z "Consequences of failure"										
Indicate the relative importance of (X) on (Y) or vice versa										
(X)	Absolute	Very Strong	Strong	Moderate	Equal	Moderate	Strong	Very Strong	Absolute	(Y)
Social Impacts	(9)	(7)	(5)	(3)	(1)	(3)	(5)	(7)	(9)	Financial Impacts
	(9)	(7)	(5)	(3)	(1)	(3)	(5)	(7)	(9)	Operational Impacts

B. Main criteria comparison with respect to each other ;

With respect to Z "Financial Impacts"										
Indicate the relative importance of (X) on (Y) or vice versa										
(X)	Absolute	Very Strong	Strong	Moderate	Equal	Moderate	Strong	Very Strong	Absolute	(Y)
Social Impacts	(9)	(7)	(5)	(3)	(1)	(3)	(5)	(7)	(9)	Operational Impacts

With respect to Z "Social Impacts"										
(X)	Indicate the relative importance of (X) on (Y) or vice versa									(Y)
Financial Impacts	(9)	(7)	(5)	(3)	(1)	(3)	(5)	(7)	(9)	Operational Impacts

With respect to Z "Operational Impacts"										
(X)	Indicate the relative importance of (X) on (Y) or vice versa									(Y)
Financial Impacts	(9)	(7)	(5)	(3)	(1)	(3)	(5)	(7)	(9)	Social Impacts

Figure 4.3 Pairwise Comparison Offered as a Matrix

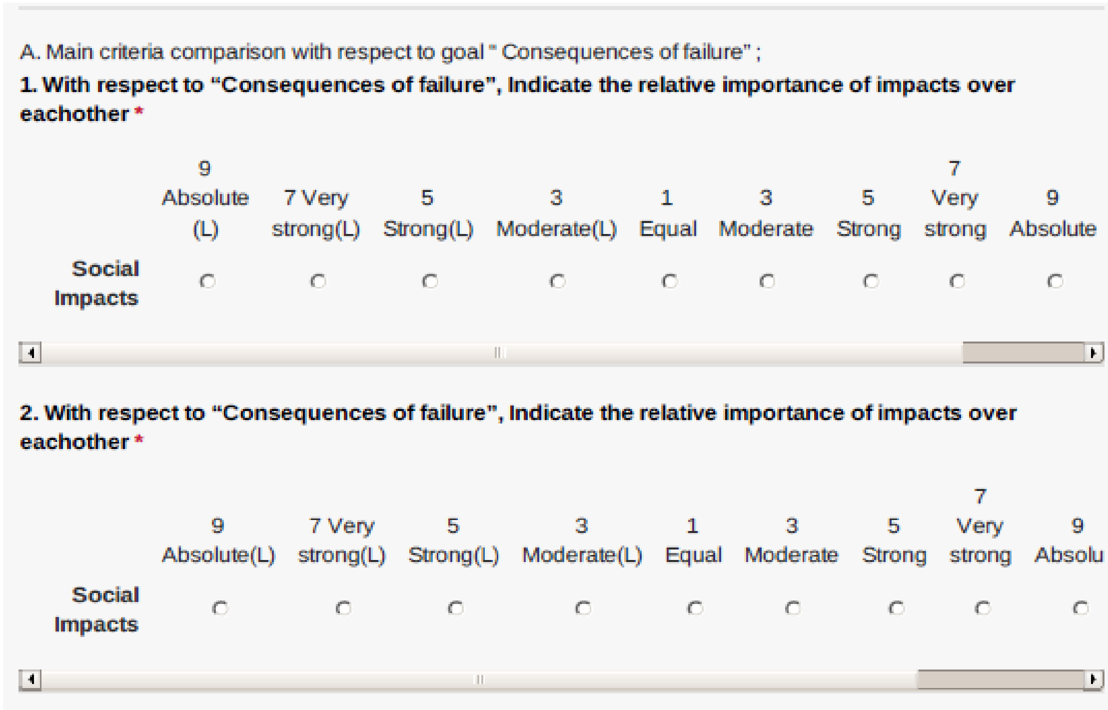


Figure 4.4 Pairwise Comparison offered in MCQ Format

The third section (Section III) poses questions regarding the Criticality index model. This section starts by the model criteria and attributes in their hierarchical form. Seven pairwise comparison matrices are provided to compare criteria with respect to goal, each other, and sub-criteria. One open ended question is provided at the end of this section.

Open Ended Questions;

Three open ended questions were provided to ensure the flexibility of including respondents' comments. Any feedback relevant to this research was accounted for in the questionnaire through regular updating. Nevertheless, some of the answers, albeit important, are out of the scope of this research and could not be accounted for. These answers however, translate the importance of the topic and the wide gap existent needed to be covered. Each question is presented with its answers to widen the horizon of area of research in subway network domain.

Q1: Are there any other impacts of failure that the survey failed to address? If yes, please indicate them.

The answer to this question included political impacts, safety posed impacts, addressing scarcity of resources in terms of spares required, and a feasibility study for excluding access to tracks to minimize safety accidents and suicidal accidents.

Q2: Based on your experience, what is the maximum allowable number of service interruptions per year to sustain a good service reputation?

The output of this question is required in the consequence of failure model development to be entered as the score for the service interruption attribute. The average answer provided is 3 interruptions per year. Whereas, some of the answers suggested the answer should be an equation representing the relation between the age of the subway and the number of interruptions accepted, such that each year of learning and operation should minimize the allowable interruptions per year. Another answer proposed a relation between the numbers of interruptions allowed and the time of interruption by hour, being in peak hour, and by day, being a weekday or holidays. This suggestion was provided by another respondent suggesting in addition to that classifying holidays based on their importance and expected increase in ridership as well.

Q3: Are there any other factors of station criticality that the survey failed to address? If yes, please indicate them.

While none of the respondents provided any direct criticality measures, most of them suggested relations to make the model more sophisticated. A respondent suggested a relation between station criticality and the day being a weekday day or a holiday. This in turns affects the ridership and the station criticality. This was seen as unnecessary since the ridership conveying a station importance is taken for all stations on a working day, thus equalizing all stations in terms of ridership. Another respondent suggested including the junction plans as a criticality attribute.

It is worth noting that all the respondents agreed to the topic novelty and sheer importance in light of the current practiced methods.

4.5 SURVEY DISTRIBUTION

The survey distribution followed three channels; distribution by hand to STM experts during meetings and interviews, communicating the survey link to transit groups on business-oriented social networking services websites, and, sending the questionnaire by email to subway and transit systems personnel. A total of 107 questionnaires were sent from which 33 replies were received with a response rate of 31%. The received questionnaires were examined thoroughly. Accordingly, 17 surveys were totally disqualified due to missing/unrealistic replies provided as illustrated graphically in Figure 4.5.

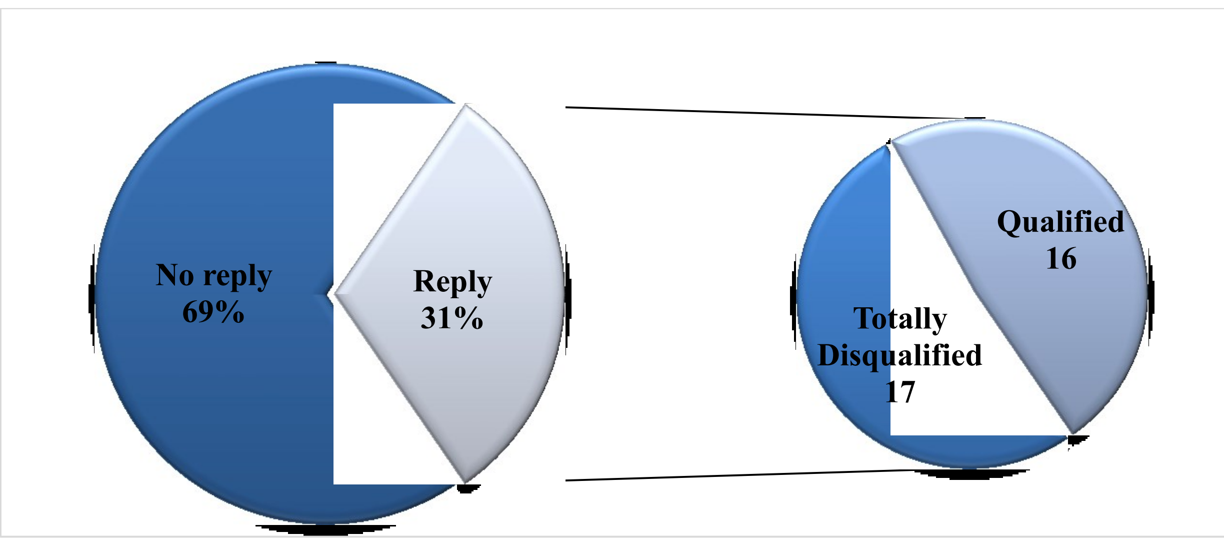
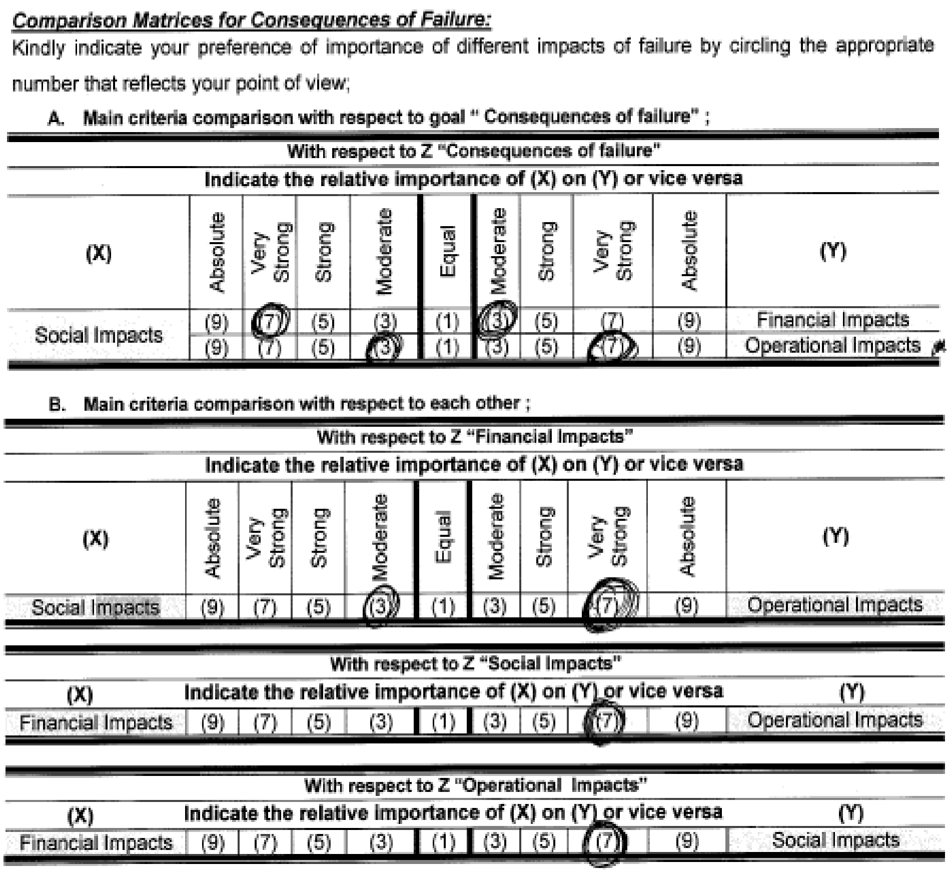


Figure 4.5 Survey Response Classification

A screenshot for a sample disqualified questionnaire is seen in Figure 4.6. The respondent provided multiple conflicting answers for the same question. From this and similar replies it was evident that the pairwise comparison concept isn't well processed within the industrial domain. This partially explains the low response and cooperation rate received from the survey. However, this feedback was used in updating the online questionnaire version to an MCQ format where the respondent is only allowed to provide one answer.



Comparison Matrices for Consequences of Failure:

Kindly indicate your preference of importance of different impacts of failure by circling the appropriate number that reflects your point of view;

A. Main criteria comparison with respect to goal " Consequences of failure" ;

With respect to Z "Consequences of failure"

Indicate the relative importance of (X) on (Y) or vice versa

(X)	Absolute	Very Strong	Strong	Moderate	Equal	Moderate	Strong	Very Strong	Absolute	(Y)
Social Impacts	(9)	(7)	(5)	(3)	(1)	(3)	(5)	(7)	(9)	Financial Impacts
	(9)	(7)	(5)	(3)	(1)	(3)	(5)	(7)	(9)	Operational Impacts

B. Main criteria comparison with respect to each other ;

With respect to Z "Financial Impacts"

Indicate the relative importance of (X) on (Y) or vice versa

(X)	Absolute	Very Strong	Strong	Moderate	Equal	Moderate	Strong	Very Strong	Absolute	(Y)
Social Impacts	(9)	(7)	(5)	(3)	(1)	(3)	(5)	(7)	(9)	Operational Impacts

With respect to Z "Social Impacts"

(X)	Indicate the relative importance of (X) on (Y) or vice versa									(Y)
Financial Impacts	(9)	(7)	(5)	(3)	(1)	(3)	(5)	(7)	(9)	Operational Impacts

With respect to Z "Operational Impacts"

(X)	Indicate the relative importance of (X) on (Y) or vice versa									(Y)
Financial Impacts	(9)	(7)	(5)	(3)	(1)	(3)	(5)	(7)	(9)	Social Impacts

Figure 4.6 A Sample Disqualified Questionnaire

The survey targeted personnel in civil engineering, and operation departments on a global level. Answers were obtained from different countries including United States, different Canadian provinces, Brazil, Singapore, and, India. The respondents varied between civil engineers, operations engineers, and division or senior managers acquiring the majority of respondents at 38% as shown in Figure 4.7. Civil engineers were next with a 33% and last was the operations engineers with 29%.

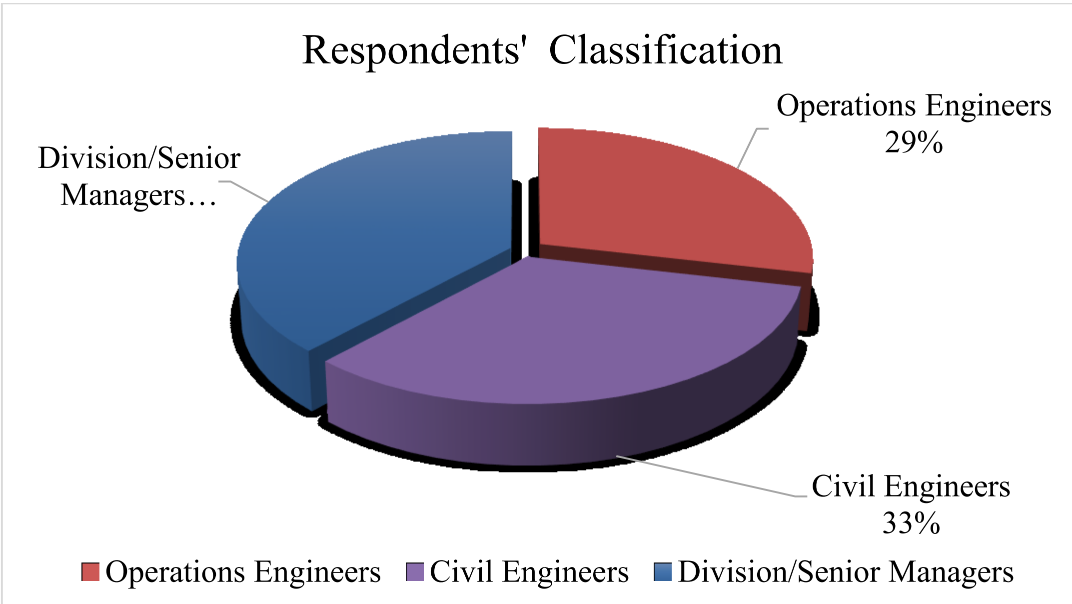


Figure 4.7 Respondents' Classification Based upon Position

Based on the provided feedback, the respondents' years of experience varied from 10 to 40 years of experience. The respondents' classification based on the years of experience is shown in Figure 4.8. Almost one third of the respondents had between 15 to 20 years of experience at 32%. Followed by respondents ranging from 20 – 24 years of experience constituting 27% of the overall respondents. Only 14% of the respondents had years of experience between 10 and 14 years. Experts with years of experience more than or equal 30 years constituted on 18% of the respondents.

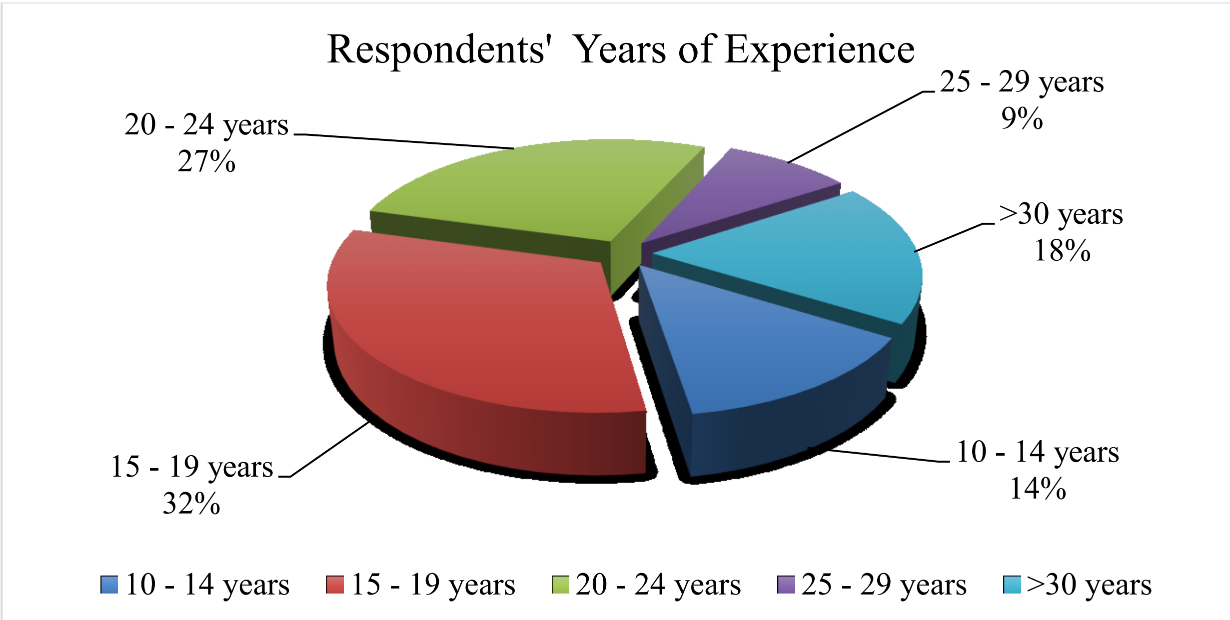


Figure 4.8 Respondents' Classification with Years of Experience

4.6 INTERVIEWS

The third type of data collection is through interviews. Structured and unstructured interviews were undertaken throughout the research with civil and operations engineers and managers in STM. The purpose was to ensure the practicality of the model for real life analysis and credibility of proposed attributes. Once the topic was well understood and the model was purposed, feedback from experts was required to construct membership functions for the inputs and outputs from the fuzzy model and establish the relation between the model variables. Based on the obtained feedback, the probability of failure sub-model is adequately presented by five membership functions as seen in Table 4.2. The membership function division complies with the inspection scale currently used by STM and with the thresholds of the reliability based model developed by Semaan (2011). Consequence of failure are represented by three membership functions, each representing the combined effect of the associated financial, operational, and social impacts as shown in Table 4.3.

Table 4.2 Probability of Failure and Assossicated Risk Level

Probability of failure	Associated risk
-0.3,0,0.3	Negligible
0.2,0.35,0.5	Minor
0.4, 0.55, 0.7	Significant
0.6, 0.75, 0.9	Critical
0.8, 1, 1.2	Serious

Table 4.3 Consequence of Failure and Associated Effects

Organizational effects	Consequence of failure		
	Critical (0.6,1, 1.4)	Tolerable (0.2,0.6,0.8)	Negligible (-0.4,0,0.4)
Financial	Financial cost will be high for repair and for giving alternative >5M$	Financial impact is a factor but usually the amount of money needed for this type of impact is easily absorbed during the current year or the following one 2M$-5M$	financial is not an impact it's covered by operational cost <2M$
Social	Reduction of customer satisfaction rate that causes their permanent loss	Reduction of customer satisfaction rate that causes temporary shifting of service	Customers are barely affected by service disruption
Operational	Failure causes a service outage affecting more than one metro line for more than 30 minutes.	Failure causes a service outage affecting a subway line in full or partial interchange outage affecting more than one line for a maximum of 15 min	Failure causing operation mode degradation for a time between 2 and 5 minutes.

The criticality index is represented by two membership functions. Based upon feedback from experts, a station is either Normal with a membership function between (-0.6, 0, 0.6) or Critical with membership function (0.4, 0.7, 1).

Experts were also asked to construct membership functions for the risk index together with the associated risk and its significance. They mostly identified risk as the urgency of an intervention action requirement. Table 4.4 shows the fuzzy risk categories identified along their membership functions and significance.

Table 4.4 The Risk Index Membership Functions and Their Sigificance.

Risk level	Membership function	Significance
Negligible	-0.25,0,0.25	No intervention required
Minor	0,0.25,0.5	Intervention required is optional, can be postponed.
Significant	0.25,0.5,0.75	Intervention is required and should be planned.
Critical	0.5,0.75,1	Obligatory intervention required, yet not urgent
Serious	0.75,1,1.75	Urgent and Obligatory intervention is required

Last, experts provided relations between the risk index model variables to construct the necessary rules required to develop the model. This resulted in the set of rules shown in Table 4.5. The provided set of rules show that the probability of failure are the main drivers for the risk index. The highest attainable level of risk as expected is the combination of the three sub-models. However, this level of risk is also triggered in case of very high failure probability or failure consequence. Criticality index is inactive as long as the probability of failure and consequence of failure are inactive. They reinforce the risk level though when any of the two sub-models approaches critical levels.

Table 4.5 Rules Used in Risk Index Development

PoF	CoF	C_R	Risk
Very low	negligible	Normal	Negligible
Low	negligible	Normal	Minor
Moderate	negligible	Normal	Moderate
Likely	negligible	Normal	Critical
Occasional	negligible	Normal	Serious
Very low	tolerable	Normal	Negligible
Low	tolerable	Normal	Minor
Moderate	tolerable	Normal	Moderate
Likely	tolerable	Normal	Critical
Occasional	tolerable	Normal	Serious
Very low	critical	Normal	minor
Low	critical	Normal	Moderate
Moderate	critical	Normal	critical
Likely	critical	Normal	Serious
Occasional	critical	Normal	Serious
Very low	negligible	critical	minor
Low	negligible	critical	Moderate
Moderate	negligible	critical	critical
Likely	negligible	critical	Serious
Occasional	negligible	critical	Serious
Very low	tolerable	critical	minor
Low	tolerable	critical	moderate
Moderate	tolerable	critical	critical
Likely	tolerable	critical	Serious
Occasional	tolerable	critical	Serious
Very low	critical	critical	moderate
Low	critical	critical	critical
Moderate	critical	critical	Serious
Likely	critical	critical	Serious
Occasional	critical	critical	Serious

4.7 SUMMARY

Several data collection techniques are used to extract the information necessary for the framework development. The data sources includes inspection reports provided by STM, survey launched online and structured and unstructured interviews. Inspection reports are provided for the period (1992-2005) and include history of most stations. It was noted that the inspections undergone by STM were discrete, random and irregular. The inspection reports however reinforced the fact that major M&R actions were done on the oldest stations in the year 2005. The second data collection methods are the surveys. The survey was first distributed by hand in interviews and pairwise was provided in a matrix form. Consequently, interviewers' feedback from this stage was considered when constructing an online more user friendly version using an MCQ format to eliminate the drawbacks of the dry run. The risk index data is mainly obtained through personal interviews. This was seen the most appropriate method of data collection following the low response rate of the survey. Data from online surveys were extracted automatically into a MS Excel® worksheet where the entire model is developed. Data from hard copy questionnaires and interviews are processed and filtered manually.

CHAPTER 5. MODEL IMPLEMENTATION

5.1 INTRODUCTION

This chapter presents a case study to demonstrate the applicability of the proposed methodology and highlight its potential benefits. Data from inspection reports is used to construct a case study segment: this case study was previously used in literature (Semaan 2011) to develop reliability performance indices. The probability of failure values are calculated and aggregated to the whole network. Next, the FANP model used in consequence of failure and criticality models is explained in details. The output of the three sub-models is integrated using the fuzzy inference engine to obtain a risk index on a network level. Finally, the budget allocation model is illustrated in the last section of this chapter.

5.2 AUTOMATED TOOL

All calculations were incorporated in a MS Excel® workbook. Figure 5.1 explains the calculations done interchangeably between MS Excel® and Matlab®. The probability of failure equations for different elements are inserted into a MS Excel® worksheet. Aggregation equations are linked through different sheets of the workbook. The questionnaire feedback is analyzed using FANP code run in Matlab®. The outputs are exported into the MS Excel® workbook. The Fuzzy Logic Toolbox in Matlab® is used to generate the risk surface using the rules and fuzzy membership functions inserted into the system. The risk index is embedded into the MS Excel® workbook as a regression equation. SolveXL®, a genetic algorithm optimization add-in for MS Excel®, is used to run the budget allocation model. The entire framework is all located in one MS Excel® workbook, easy to use and implement. Screenshots for the calculations follow each model.

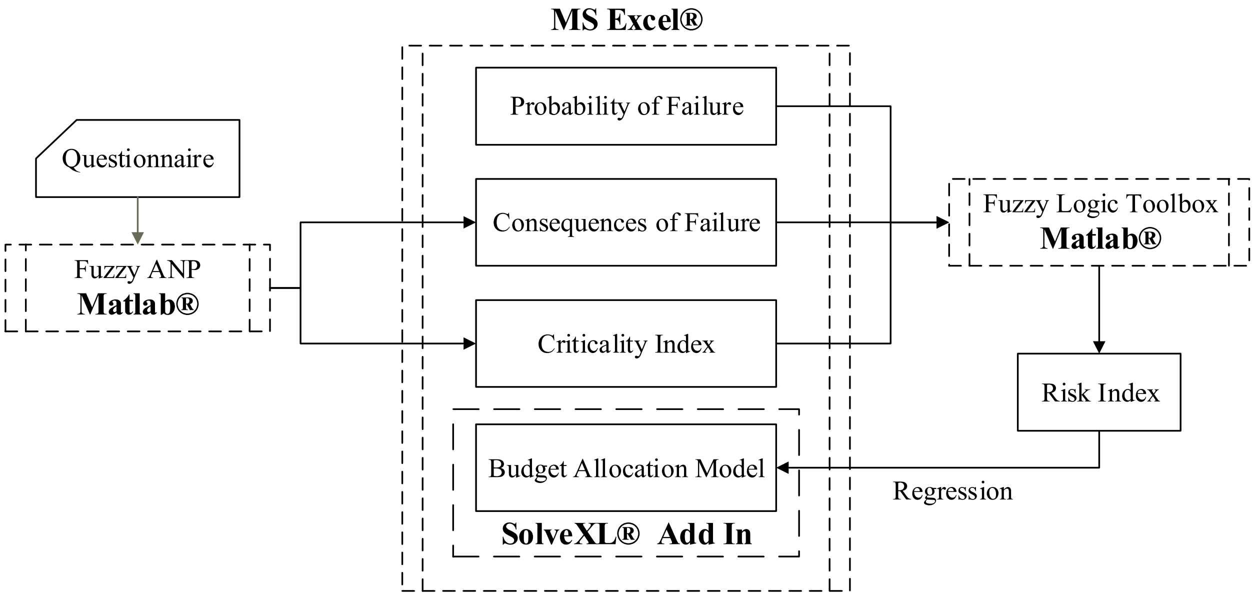


Figure 5.1 Automated Steps for the Proposed Methodology

5.3 PROBABILITY OF FAILURE SUB-MODEL

The "Reno-Station II" program was executed in 2005 and aimed at renovating all stations constructed in the year 1966, improving the overall system integrated performance up to 90% of the total performance. Furthermore, the remaining service life (after M&R) is considered 90 years proportional to the adjusted new performance instead of 100 years, as the case of new concrete. The probability of failure sub-model starts by calculating the PoF values for elements in each system following the network hierarchy presented in Figure 3.2 and Equation (3.4) to Equation (3.8). The reliability values of the different elements are calculated using the model proposed by (Semaan, 2011) using the year 2014 as the calculation year. Moreover, this value is updated for any M&R actions undergone since the last inspection, which resulted in an updated performance of 0.9 for the M&R year as explained earlier. Once the reliability value per element is calculated, probability of failure of each element can be easily calculated as the inverse of reliability as shown in Equation (3.1). The next step is calculating probability of failure of systems (STA, TUN, and AUX) through upwards aggregation and the parallel-series network modeling technique. Logical systems configuration deducted in Section 3.3 and presented in Figure 3.4 and Figure 3.5 are used to construct the systems equations. It is noted that equations used in upwards aggregation in the reliability model are different from those used in the Probability of failure model due to the difference in significance between the reliability and the probability of failure values. Probability of failure of STB is concluded followed by PoF for lines and finally the network (in this case study, the segment). Model equations are incorporated in a nested MS Excel® workbook.

5.3.1. Probability of Failure of Stations System

A subway station is composed of walls (interior and exterior), slabs (interior and exterior), and, stairs (interior and exterior). Acronym used for calculations are shown in Table 5.1.

Table 5.1 Acronym of Station Elements

Element	Acronym
Interior Slab	SI
Exterior Slab	SE
Interior Wall	WI
Exterior Wall	WE
Interior Stairs	STI
Exterior Stairs	STE

Probability of failure is calculated for all elements in a station using Equation (3.1) for all station floors. Results are then aggregated using parallel-series network technique based on the elements configuration as presented in Chapter 3 to compute the overall probability of failure of station systems. Results are presented in Table 5.2. Probability of failure values of elements are considerably low, ranging between zero and a maximum of 0.381 for element SE3 in STA 4. Based on the PoF values per elements, the average PoF value is calculated at 0.0464.

Table 5.2 Probability of Failure for Station Systems and their Elements

Floor	Element	STA 1	STA 2	STA 3	STA 4	STA 5	STA 6
0	SE0	0	0	0	0	0	0
	SI0	0	0	0	0	0	0
	WE0	0	0	0	0.052	0	0
	WI0	0	0	0	0.052	0	0
	STE0	0	0	0	0	0	0
	STI0	0	0	0	0	0	0
1	SE1	0.1193	0	0.052	0.103	0.119	0
	SI1	0	0	0.086	0.086	0	0.2
	WE1	0.0859	0	0.052	0.086	0.119	0.2
	WI1	0.0859	0	0.152	0.168	0	0.119
	STE1	0	0	0	0	0	0.168
	STI1	0	0	0	0	0	0
2	SE2	0	0	0.086	0.069	0.119	0.185
	SI2	0	0	0	0.017	0	0
	WE2	0.1026	0	0	0	0	0.168
	WI2	0	0	0.086	0	0	0.168
	STE2	0	0	0	0.086	0	0
	STI2	0	0	0	0	0	0
3	SE3				0.381	0	
	SI3				0.293	0	
	WE3				0.323	0	
	WI3				0.152	0.119	
	STE3				0.086	0	
	STI3				0	0	
4	SE4				0.069		
	SI4				0		
	WE4				0.052		
	WI4				0		
	STE4				0		
	STI4				0		
PoF		0.25	0	0.268	0.673	0.224	0.513

Equation (3.4) is used to calculate the probability of failure per station based on the elements PoF. The six stations under study show a wide range of PoF values ranging from the minimum of zero for STA 2 to the maximum of 0.673 for STA 4 which is considered relatively high. The three stations STA1, STA 2, STA 3 and STA 5 have a low probability of failure with a maximum value of 0.268. STA 4 however has an alarming PoF of 0.673. This station has the maximum number of floors and thus elements, in addition, the highest elements' PoF values are within this station. While the slabs and stairs systems are considered redundant systems, the wall systems operate in series and thus their failure entails the failure of the overall station system. This logic explains the high value of PoF which is the ripple effect of the small PoF values for the series elements mainly.

5.3.2. Probability of Failure of Tunnel System

A tunnel system (TUN) is composed of three elements operating in series; Dome (D), a Bottom Slab (BS), and Walls (W). Calculations for tunnel element probability of failure are shown in Equation (3.5) and presented in Table 5.3.

Table 5.3 Probability of Failure of Tunnel Systems and their Elements

TUN #	D	W	BS	Aggregated
TUN 1	0.068956	0.051915	0	0.117
TUN 2	0.119281	0.068956	0	0.180
TUN 3	0.085864	0.102639	0	0.179
TUN 4	0.085864	0.085864	0	0.164
TUN 5	0.068956	0.085864	0	0.149
TUN 6	0	0	0	0

All tunnel elements have very low PoF values ranging from 0 to a maximum of 0.11 which is still a very low value. Consequently, the aggregated PoF values for the TUN system was very low ranging from zero to a maximum value of 0.18.

5.3.3. Probability of Failure of Auxiliary Structures System

Auxiliary Structures are composed of walls (W), Top Slabs (TS), and Bottom Slabs (BS). In which the top and bottom slab operate in parallel together and in series with the wall systems. This is translated in Equation (3.6) used to obtain the PoF values presented in Table 5.4. the PoF values for the different auxiliary structures elements is very low and mostly zero, consequently, the aggregated PoF values for auxiliary structures were very low.

Table 5.4 Probability of Failure of Auxiliary Structure Systems and their Elements

	W	TS	BS	Aggregated
AS1	0.09	0	0	0.09
AS2	0	0	0	0
AS3	0	0	0	0
AS4	0.17	0.07	0	0.23
AS5	0	0	0	0
AS6	0	0	0	0

5.3.4. Probability of Failure for Lines

A generic subway network line is composed of all stations, tunnel, and auxiliary structure systems operating on the line. These systems together operate in series whereas; the composition of each system operates in parallel as illustrated in Figure 3.5 and shown in Equation (3.7). The line probability of failure is the aggregated probability of failure of the station, tunnels, and auxiliary structures composing it. The resulted predicted PoF values for the three line segments under consideration are presented in Table 5.5.

Line A has a negligible PoF value of 0.0038. Line C has the highest PoF value of 0.513 which is the adjacent PoF value for the only station composing the line. Line B has an overall PoF value of 0.1718. This PoF value is the integration of the PoF values of the six systems composing the line (STA 4, STA 5, TUN 4, TUN 5, AUX 4, and AUX 5).

Table 5.5 Lines Probability of Failure

	STA	TUN	AUX
STB 1	0.2501	0.1173	0.0859
STB 2	0.0000	0.1800	0.0000
STB 3	0.2685	0.1797	0.0000
PoF line A	0.0038		
STB 4	0.6732	0.1644	0.2257
STB 5	0.2243	0.1489	0.0000
PoF line B	0.1718		
STB 6	0.5130	0.0000	0.0000
PoF line C	0.5130		

STA 4 has an alarmingly high PoF, yet, when analyzing on a strategic level, this PoF is averaged and absorbed by the low PoF values for the adjacent systems on this line. As stated earlier, stations systems operate in parallel, indicating the line is only in a critical condition when all the stations falling on it have high PoF values. This concept is strongly illustrated with the PoF values of Line B and line C in comparison to the PoF of STA 4 and STA 5 respectively and can be seen in Figure 5.2 and Figure 5.3.

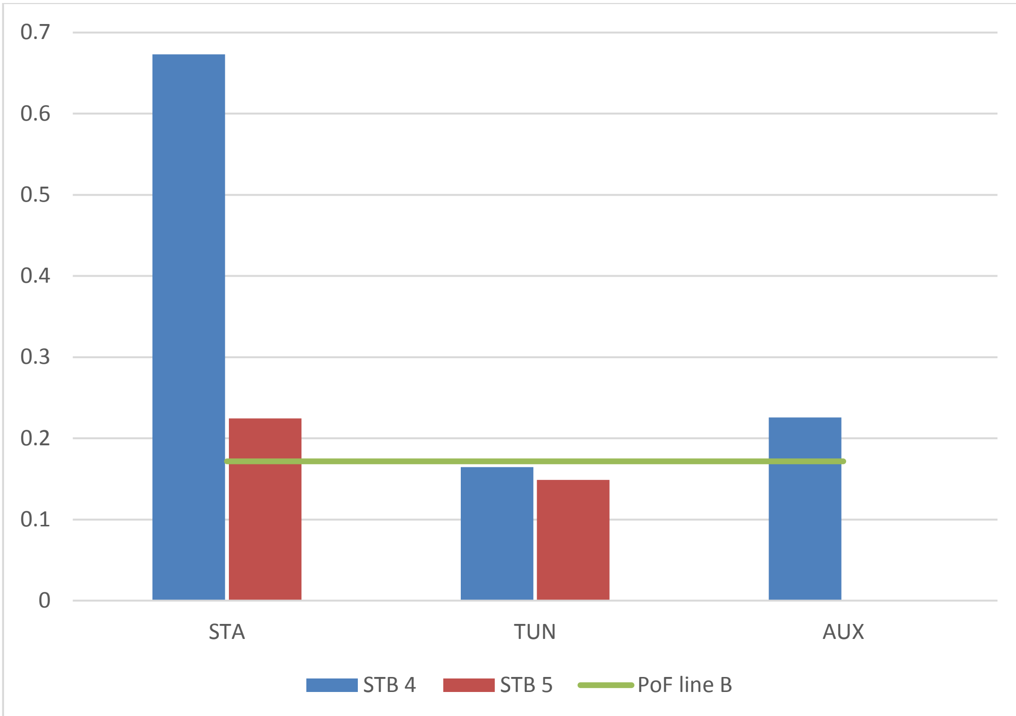


Figure 5.2 PoF values for Line B and its Systems

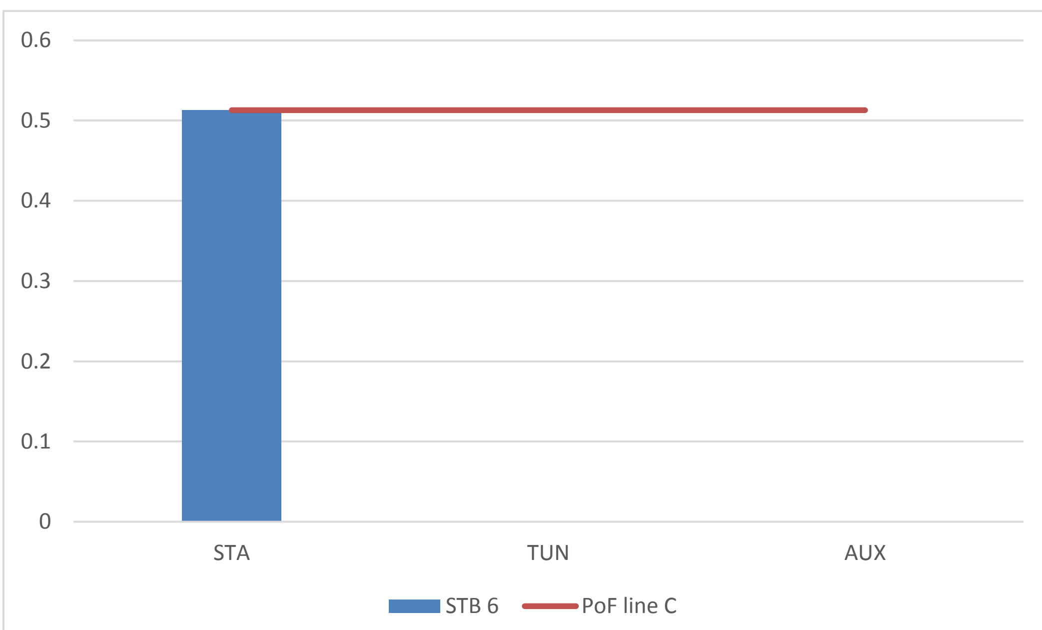


Figure 5.3 PoF values for Line C and its Systems

5.3.5. Probability of Failure of Segment

The subway segment under study is composed of three interconnecting lines. Probability of failure of the segment is the aggregated value for the Probability of failure of lines composing the segment, lines A, B, and C based on Equation (3.8) and shown here in Equation (5.1). In a subway network, lines operate in parallel: therefore, the subway segment will only fail when all of its lines fail. Therefore, a respectively high line PoF is affected by the adjacent lines PoF values. In our case, the segment PoF is negligible due to the combined effect of Low PoF for lines operating in parallel.

$P_{\text{Segment}} = \prod_{3}^{i=1} P_{\text{Linei}} = 0.5130 * 0.1718 * 0.0038 = 0.0003$

Figure 5.4 illustrates the probability of failure calculation workbook for elements per station. For the six stations under study, the ideal performance index ($P_I I$) is calculated per all station system elements. The updated performance index (P_I UPC) is also calculated per station elements based upon the data available from inspection reports. These two indices are then used to compute the PoF per element as identified by the red rows. PoF per station system is calculated in the last column by integrating PoF values for elements using the parallel-series modeling technique.

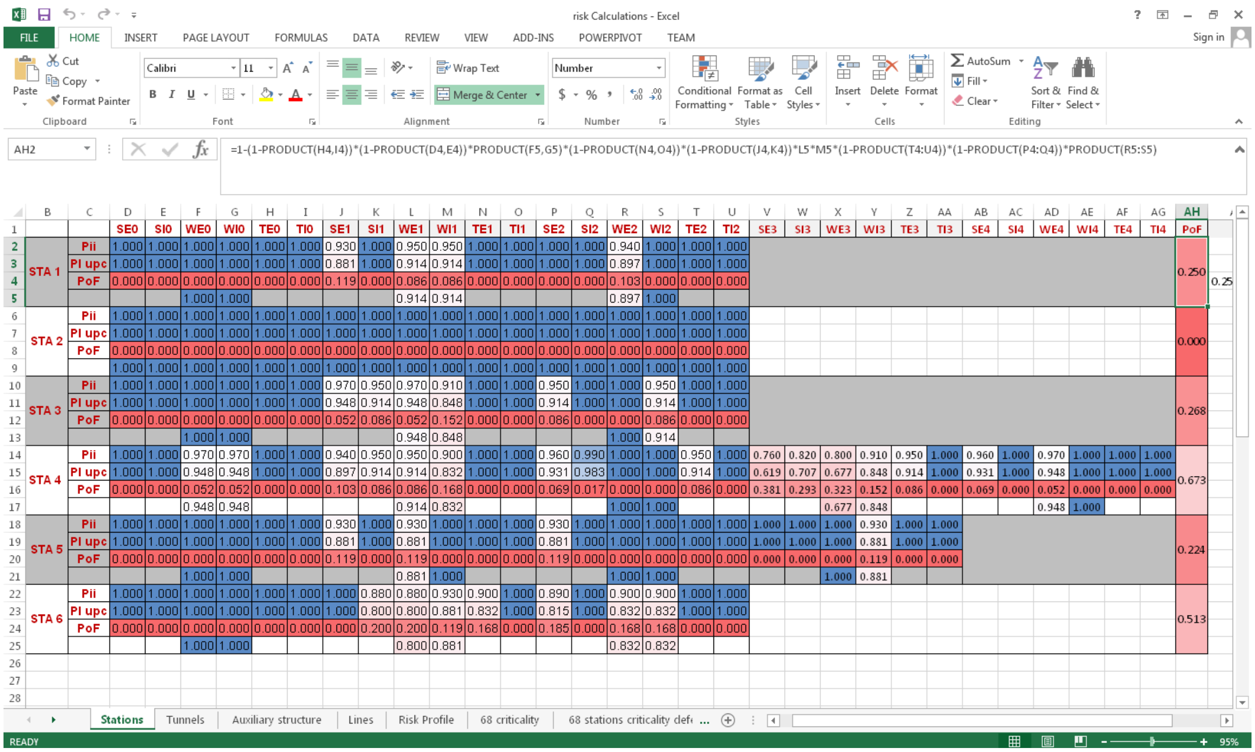


Figure 5.4 Screenshot for Probability of failure Calculation Sheet

5.4 CONSEQUENCE OF FAILURE SUB-MODEL

The consequence of failure sub-model follows three main steps to calculate the CoF score per subway element. Sample screenshot for the calculation sheet is shown in Figure 5.4. In the financial impacts cluster, the expected revenue loss is identified per element and then normalized based upon the maximum value available for the network under study. Repair cost score is calculated based upon the repair option selected and normalized to the maximum score which is the replacement option. These steps are repeated for the social and operational impacts of failure. Using the weights obtained from FANP calculations, the CoF value per element is calculated as seen in the last highlighted column.

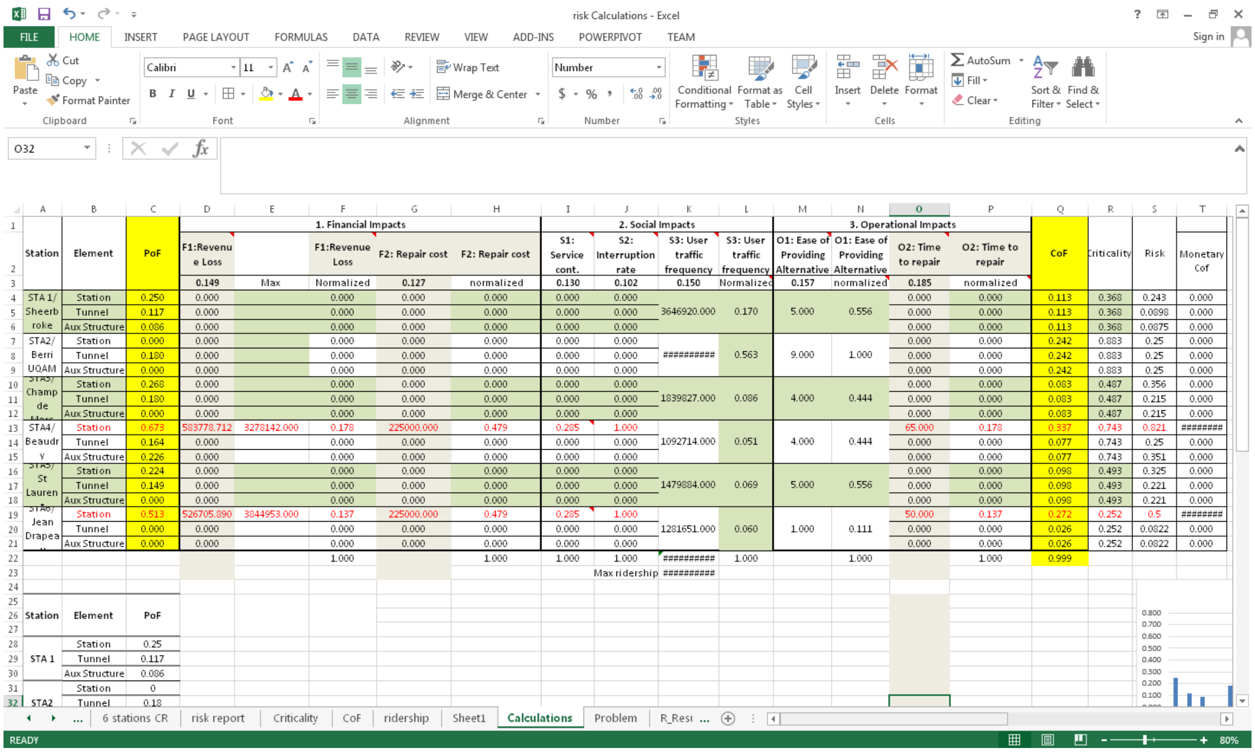


Figure 5.5 Screenshot for Consequence of Failure Calculation Sheet

Calculate Consequence of Failure weights (CW_i) **.**

This step includes extracting data from questionnaires to use as input in the FANP model. Experts' feedback was extracted manually in case of hard copy and email questionnaires and extracted automatically in case of online questionnaires to a MS Excel® worksheet. Once all data is assembled correctly in the work sheet, this file is imported into MATLAB® where the FANP code was written. Appendix B contains the code used for FANP calculations in MATLAB®. A basic FANP code available online was edited and tested to suit our case study and number of attributes. This step resulted in the global weights for CoF criteria and the local and global weights for CoF attributes as presented in Table 5.6.

Table 5.6 Local and Global Weights of Consequence of Failure Sub-Model

Main Criteria	Global weight	Attributes	Global Weight	Local weight
Financial Impacts	27.65%	F1:Revenue Loss	14.96%	54.12%
		F2: Replacement/repair cost	12.68%	45.87%
Social Impacts	38.21%	S1: Service continuation	12.95%	33.90%
		S2: Interruption rate	10.22%	26.73%
		S3: User traffic frequency	15.04%	39.36%
Operational Impacts	34.14%	O1: Ease of Providing Alt.	15.69%	45.96%
		O2: Time to repair	18.45%	54.04%

Model Testing

The local and global weights presented in Table 5.6 and illustrated graphically in Figure 5.6 were tested using experts opinion. This was seen as the most appropriate testing method in light of data scarcity and low cooperation rate. Accordingly, the model was presented to and approved by an STM personnel in charge of the network's risk assessment. He verified the model output was legitimate and adequately conveys the network studied.

Figure 5.6 illustrates graphically the global weights for the CoF model main criteria. It can be seen that social impacts of failure had the highest importance between experts with a value of 38% followed by operational impacts at 34% and last, financial impacts at 27.65%. These values conform to the current approach followed by STM where stations with higher effect on customers acquire a higher priority for rehabilitation to ensure high customer satisfaction.

Moreover, the membership functions implications provided by experts stated that financial impacts are usually covered by operational costs for moderate and low consequence of failure.

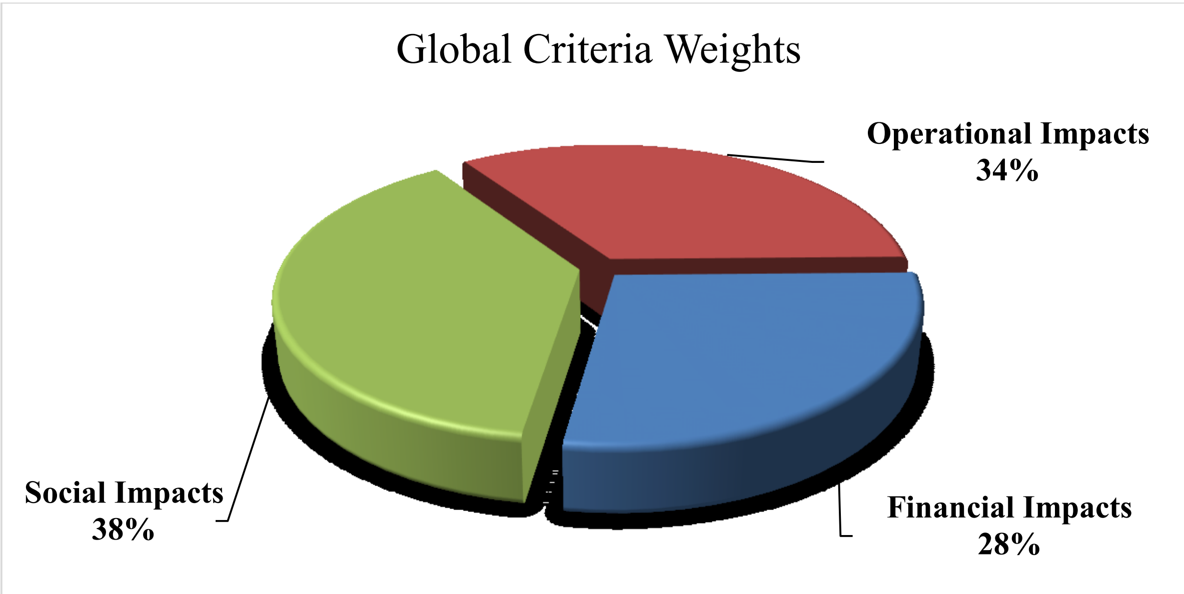


Figure 5.6 Global Criteria Weights in CoF Sub-Model

Attributes and criteria weights are shown graphically in Figure 5.7 and Figure 5.8, time to repair had the highest global weight of 18.45%. This is understandable since time to repair has direct impact on revenue loss, interruption rate, and the user traffic frequency. Ease of providing alternative and user traffic frequency came next with close global weight values of 15.69% and 15.04% respectively. Both sub-attributes are seen as interrelated, since a decent alternative ensures customers are minimally affected by the service interruption. Revenue loss has a global weight of 14.96%, based on experts' feedback, operational costs are usually used to cover moderate to low financial impacts of failure, and this explains the somehow moderate global weight of the revenue loss. Replacement/repair cost and service continuation are next with close global weights followed by interruption rate having the least weight of 10.22%.

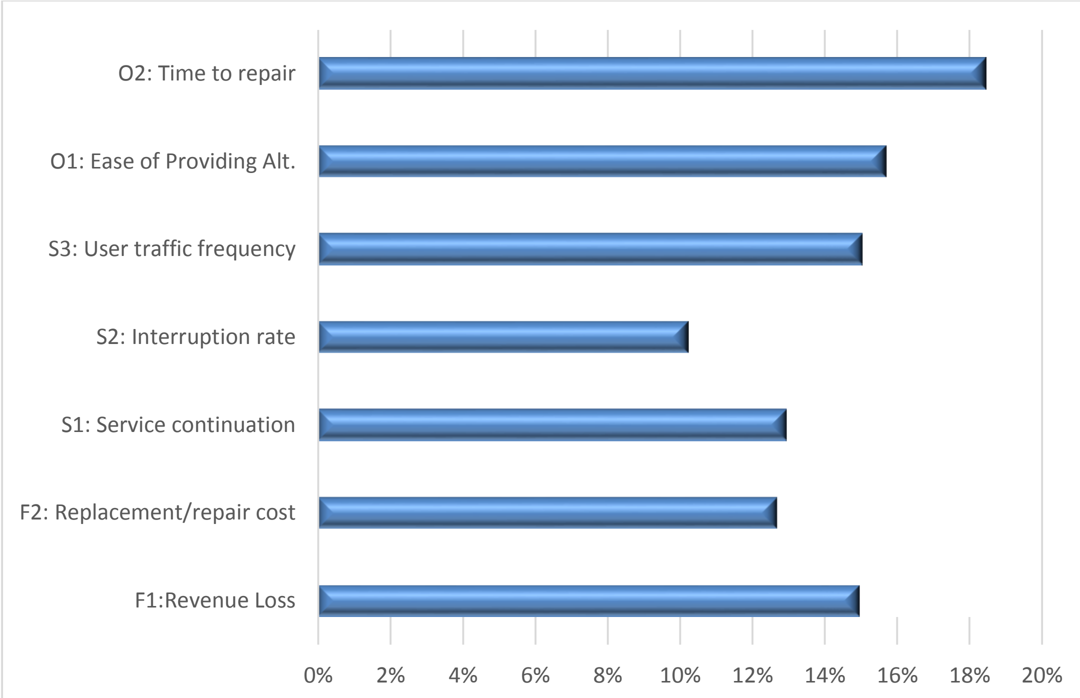


Figure 5.7 CoF Attributes Global Weights

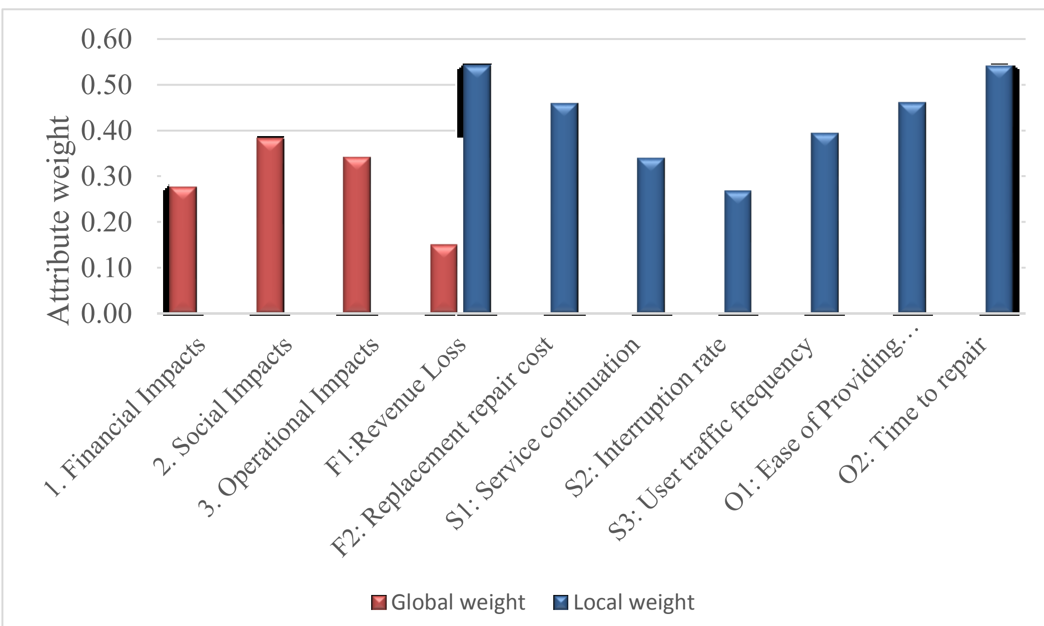


Figure 5.8 Consequence of Failure Local and Global Weights Plot

Compute the severity scores (Ss_i)

Scores for consequence of failure criteria are obtained using actual metro statistics available online, literature review, and inspection reports. Due to the high variability in the selected attributes nature, all scores were individually normalized based on the highest score provided per network. This ensures the proportionality of the consequence of failure calculations especially in the studied segment in our case study. Table 5.7 identifies each failure impact, the attributes considered in the analysis and a detailed description of each attribute. The score of each attribute is normalized based upon the network under study and the maximum and minimum score thresholds identified.

The maximum allowable number of interruptions per year is averaged from experts' feedback in the questionnaire. Maximum time to repair is assumed 365 days equivalent to one year since the model analysis in done on an annual basis. User traffic frequencies for different stations are available online through reports and data published by STM.

When calculating financial impacts of failure, loss of revenue can be easily estimated using Equation (3.9). The replacement/repair cost however requires a different approach. Consequently, five generic M&R treatment levels are considered in the analysis based upon data from inspection reports, actual current network data, and literature review.

(Farran, 2006) derived cost elements based upon different documents provided by STM and prepared by engineering firms, these are used as guideline to generate the different treatment actions and the associated cost. Each treatment action is associated by expected cost in \$/m^{2}and expected level of improvement, assumed based on literature review.

Table 5.7 Consequence of Failure Definition and Scales

Failure Impact	Attribute	Definition	Score	
			Maximum	Minimum
Financial	Repair/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, factor of user traffic frequency, time to repair and fare	100%	0%
Operational	Ease of providing alternative	Measured by the decision maker based on the available bus stations per area	Normalized based on maximum and minimum number of bus stops/station/network	
	Time to repair	Required time to return the failed component to a full functioning state	365 days	0 days
Social	User Traffic Frequency	The number of users accessing the station and affected by the service interruption	Normalized based on maximum ridership per network	
	Interruption Rate	Defined by the decision maker as the maximum allowable number of interruptions per year	6	0
	Service Continuation	Estimated based on element configuration and decision maker	Full interruption = 100%	No interruption = 0%

Table 5.8 presents the generic M&R actions used in the analysis and their associated descriptions. Each M&R action data is used to input the consequence of failure model scores, where applicable, whereas the budget allocation model will be responsible of identifying the optimum strategy to be followed to achieve the stated budget. This table will be referred to later in the budget allocation model.

In the presented case study and based on the probability of failure values, STA 4 and STA6 only need intervension. STA 6 is currently under renovation, the actual renovation plan was considered in the model calculations. The station will be repaired during weekends only to minimize the service interruptions during which new shuttle busses will be provided. The renovations will be done on a time span of 25 weekends. Therefore, the interruption time is computed as 25*2=50 days. The service continuation is the percentage of days per week during which the service is unavailable, for this case the service will be disrupted for 2 days each week, a percentage of 2/7=0.285 is used. The degree of interruption refers to the nature of interruptions requiring total, partial, or no station closure at all. STA 4 calculations are similar to that of STA 6 , where the interruptions are assumed in weekends only but since STA 4 has a higher PoF , it can be safe to assume the time to repair will be longer with a value equals to the difference in probabilituy of failure values calculated. Action 4 details are used as the scores input for STA4 and STA 6 in the CoF model calculations.

Table 5.8 M&R Treatments and their Effects

Action	Description	% Improvement	Expected Cost $/m^2
1	Do nothing	0	0
2	Preventive Maintenance	15%	12000
3	Minor Rehabilitation	40%	200000
4	Major Rehabilitation	65%	225000
5	Element Replacement	100%	500000

User traffic frequency for all stations was obtained from online data available and normalized based on the total ridership of the network under study. Calculations for computing consequence of failure criteria scores and normalizing them is presented in Table 5.9 for financial impacts of failure. The actual value for revenue loss per station and the expected repair cost are shown. Normalized values for each of the financil impacts sub-attributes are also presented. Calculations are done using MS Excel® workbook where the entire framework calulations are located.

Table 5.9 Financial Impacts Scores

Station	System	1. Financial Impacts			
		F1:Revenue Loss		F2: Repair cost	
		Actual Value	Normalized	Actual Value	Normalized
STA 1	Station	0.000	0.000	0.000	0.000
	Tunnel	0.000	0.000	0.000	0.000
	Aux	0.000	0.000	0.000	0.000
STA2	Station	0.000	0.000	0.000	0.000
	Tunnel	0.000	0.000	0.000	0.000
	Aux	0.000	0.000	0.000	0.000
STA3	Station	0.000	0.000	0.000	0.000
	Tunnel	0.000	0.000	0.000	0.000
	Aux	0.000	0.000	0.000	0.000
STA4	Station	583779	0.178	225000	0.479
	Tunnel	0.000	0.000	0.000	0.000
	Aux	0.000	0.000	0.000	0.000
STA5	Station	0.000	0.000	0.000	0.000
	Tunnel	0.000	0.000	0.000	0.000
	Aux	0.000	0.000	0.000	0.000
STA6	Station	526706	0.137	225000	0.479
	Tunnel	0.000	0.000	0.000	0.000
	Aux	0.000	0.000	0.000	0.000

Scores for social impacts of failure are presented in Table 5.10. For each station, the service continuation value is assigned based on the M&R scenario selected.

Table 5.10 Social Impacts Scores

Station	System	2. Social Impacts			
		S1: Service cont.	S2: Interruption rate	S3: User traffic frequency	
				Actual Value	Normalized
STA 1	Station	0	0	3646920	0.17
	Tunnel	0	0		
	Aux	0	0		
STA2	Station	0	0	12053754	0.563
	Tunnel	0	0		
	Aux	0	0		
STA3	Station	0	0	1839827	0.086
	Tunnel	0	0		
	Aux	0	0		
STA4	Station	0.285	1	1092714	0.051
	Tunnel	0	0		
	Aux	0	0		
STA5	Station	0	0	1479884	0.069
	Tunnel	0	0		
	Aux	0	0		
STA6	Station	0.285	1	1281651	0.06
	Tunnel	0	0		
	Aux	0	0		

In our case study segment, STA 4 and STA 6 required rehabilitation. Since STA 6 is currently under rehabilitation, the actual rehabilitation was selected. STA 6 is undergoing rehabilitation actions only on weekends to minimize the service disruption. Consequently, time to repair is calculated only on weekends for every given week, giving an overall service continuation percentage of 2/7=0.285. While the rehabilitation actions are performed, a whole service disruption is expected and the entire station is closed, thus the interruption rate is total (1.0) for weekend rehabilitation activities. Operational impacts of failure scores are presented in Table 5.11.

Table 5.11 Operational Impacts Scores

Station	System	3. Operational Impacts			
		O1: Ease of Providing Alt.		O2: Time to repair (days)	
		Actual Value	Normalized	Actual Value	Normalized
STA 1	Station	5.000	0.556	0.000	0.000
	Tunnel			0.000	0.000
	Aux			0.000	0.000
STA2	Station	9.000	1.000	0.000	0.000
	Tunnel			0.000	0.000
	Aux			0.000	0.000
STA3	Station	4.000	0.444	0.000	0.000
	Tunnel			0.000	0.000
	Aux			0.000	0.000
STA4	Station	4.000	0.444	65.000	0.178
	Tunnel			0.000	0.000
	Aux			0.000	0.000
STA5	Station	5.000	0.556	0.000	0.000
	Tunnel			0.000	0.000
	Aux			0.000	0.000
STA6	Station	1.000	0.111	50.000	0.137
	Tunnel			0.000	0.000
	Aux			0.000	0.000

Ease of providing alternative is calculated based on the number of bus stops surrounding the metro station and normalized based upon the maximum number of stops available per station per study segment. Time to repair is the actual time required to return the failed component to a full functioning state. Time to repair of STA 4 and STA6 are assumed proportional to their PoF values.

Compute total Consequence of Failure Score (CF_i) per element

This is the last step in the CoF sub-model. CoF score per element is calculated as the weighted product of each attribute using the weights and scores calculated in the previous steps. Table 5.12 presents the normalized scores of the different consequence of failure attributes along with their global weights. The computed overall consequence of failure score per element is also presented in the last column. As expected, the highest CoF values are for stations (STA 4) and (STA 6) in which a high PoF value have been recorded and thus, an M&R action is triggered. From this table, it can be seen that CoF values are equal for all systems in a given station building when no high PoF values are recorded. A high PoF value triggers an M&R action and thus an increased CoF value for only the system with the failed component and not for the entire STB system. The consequence of failure indices for all elements is minute, except for STA4 and STA6 where a rehabilitation action is considered, thus a considerable CoF index is obtained in both cases. For STA4, a CoF of 0.337 is obtained which confirms to the rehabilitation action done. Whereas STA6 had a lower CoF index of 0.272.The CoF sub-model values were revised and approved by experts.

Table 5.12 Consequence of Failure Sub-model Calculations

Segment	System	F1	F2	S1	S2	S3	O1	O2	CoF
Attribute Weight		0.149	0.127	0.130	0.102	0.15	0.157	0.185	
STB 1	Station	0.000	0.000	0.000	0.000	0.17	0.556	0.000	0.133
	Tunnel	0.000	0.000	0.000	0.000			0.000	0.133
	Aux	0.000	0.000	0.000	0.000			0.000	0.133
STB2	Station	0.000	0.000	0.000	0.000	0.563	1.000	0.000	0.242
	Tunnel	0.000	0.000	0.000	0.000			0.000	0.242
	Aux	0.000	0.000	0.000	0.000			0.000	0.242
STB3	Station	0.000	0.000	0.000	0.000	0.086	0.444	0.000	0.083
	Tunnel	0.000	0.000	0.000	0.000			0.000	0.083
	Aux	0.000	0.000	0.000	0.000			0.000	0.083
STB4	Station	0.178	0.479	0.285	1.000	0.051	0.444	0.178	0.337
	Tunnel	0.000	0.000	0.000	0.000			0.000	0.077
	Aux	0.000	0.000	0.000	0.000			0.000	0.077
STB5	Station	0.000	0.000	0.000	0.000	0.069	0.556	0.000	0.098
	Tunnel	0.000	0.000	0.000	0.000			0.000	0.098
	Aux	0.000	0.000	0.000	0.000			0.000	0.098
STB6	Station	0.137	0.479	0.285	1.000	0.06	0.111	0.137	0.272
	Tunnel	0.000	0.000	0.000	0.000			0.000	0.026
	Aux	0.000	0.000	0.000	0.000			0.000	0.026

5.5 CRITICALITY INDEX SUB-MODEL

Montreal subway has 68 stations spreading on four lines and covering the north, east, and center of the Island of Montreal with connections to Longueil, and Laval. Criticality index measures the respective station importance based on a number of attributes including the station location in proximity to different attractions. Accordingly, the Montréal subway map was studied in depth. All possible points of interest accessible by a subway station or a bus from a subway station were identified and grouped by their relevance to three groups of locations. A station location is either in proximity to vitalities, recreational areas, or residence areas. Table 5.13 lists the full description of existing points of interest in Montreal subway clustered by their attraction type and grouped based on their relevance into three main groups.

The criticality model phases are similar to those of the consequence of failure model. First, local and global weights are obtained using input from questionnaires and analyzed using FANP. Second, scores for different attributes are calculated and normalized based on the maximum and minimum values existent in the network understudy, where applicable. Last, scores and weights are combined to compute the final criticality index per station. In the Criticality Index model, normalization per score is only applicable in two attributes, number of exits and number of levels. The maximum number of exits considered equals to the maximum number of exits in a station on the selected network for study. In our case, this number is equivalent to 9 exits as concluded from the structural drawings of the stations. Maximum number of levels is calculated likewise, based on the maximum number in the network under study. The Criticality index model operates on the stations system level as explained in the methodology chapter.

Table 5.13 Attractions Definition by Group

Attraction type	Points of Interest	Grouping
Main Touristic Attractions	Museums, Theatres, Centre Infotouriste, Old Montreal and 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	
Businesses	Locations for Commerce Chambers, Quartier International de Montréal	Vitalities
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

Calculate Criticality Index weights$(\boldsymbol{C_R W_i})$

The third section of the questionnaire presents questions for rating criticality attributes with respect to their importance. Pairwise comparison matrices from the questionnaires are processed in MATLAB® to obtain local and global weights for attributes using FANP with application to FPP. The FANP MATLAB® code was used for the Criticality index calculations following the same steps listed earlier. Local and global attributes weights are presented in Table 5.14. The three main criteria comprising the model had close weight values ranging from 31.82% to a maximum of 35% for station location. Attributes scores on the other hand show great variability in terms of global weight as shown in Figure 5.9 and Figure 5.10. An intermodal station has the highest global weight of 24.37%. This is expected since an intermodal station presents an intersecting number of lines and/or transportation modes which implies higher traffic frequency and consequently higher station importance.

Table 5.14 Criticality Attributes Weights Obtained Using FANP

Main Criteria	Global weight	Attributes	Global weight	Local weight
Station Characteristics (C)	31.82%	C1: Number of exits	15.81%	49.68%
		C2: Number of Levels	16.01%	50.31%
Station nature of use (N)	33.13%	N1: End Station	10.67%	30.45%
		N2: Intermodal Station	24.37%	69.55%
Station Location (L)	35.04%	L1: Recreational	06.29%	18.99%
		L2: Residence	09.42%	28.45%
		L3: Vitalities	17.41%	52.55%

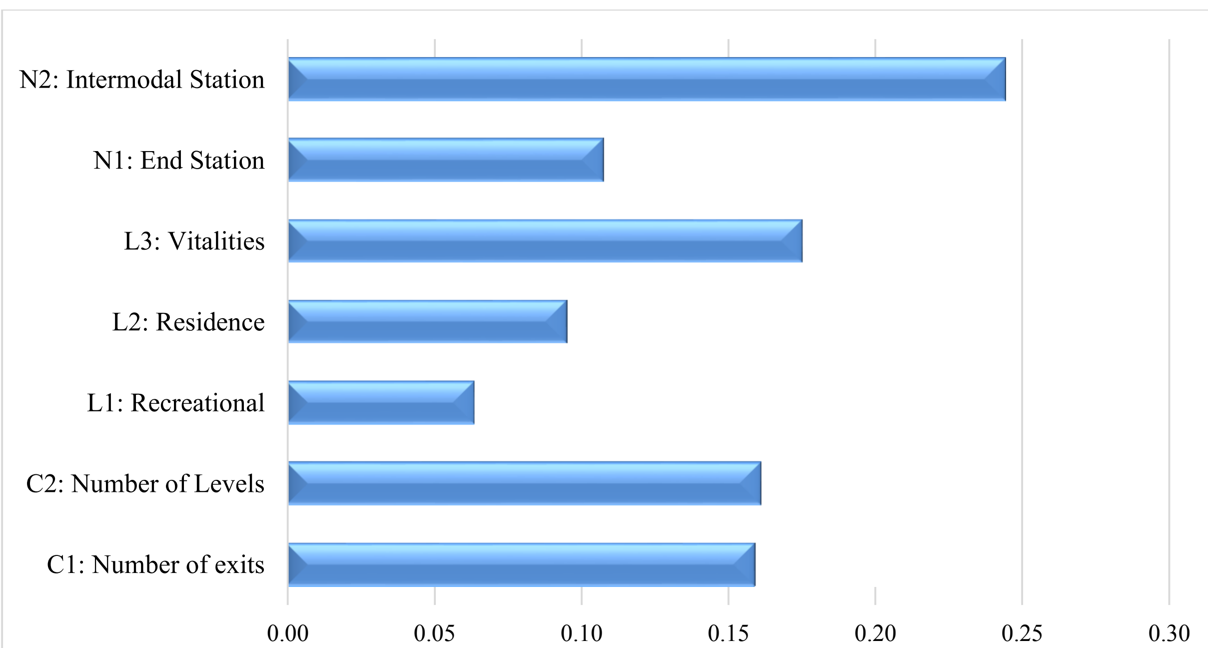


Figure 5.9 Criticality Index Attributes Global Weights

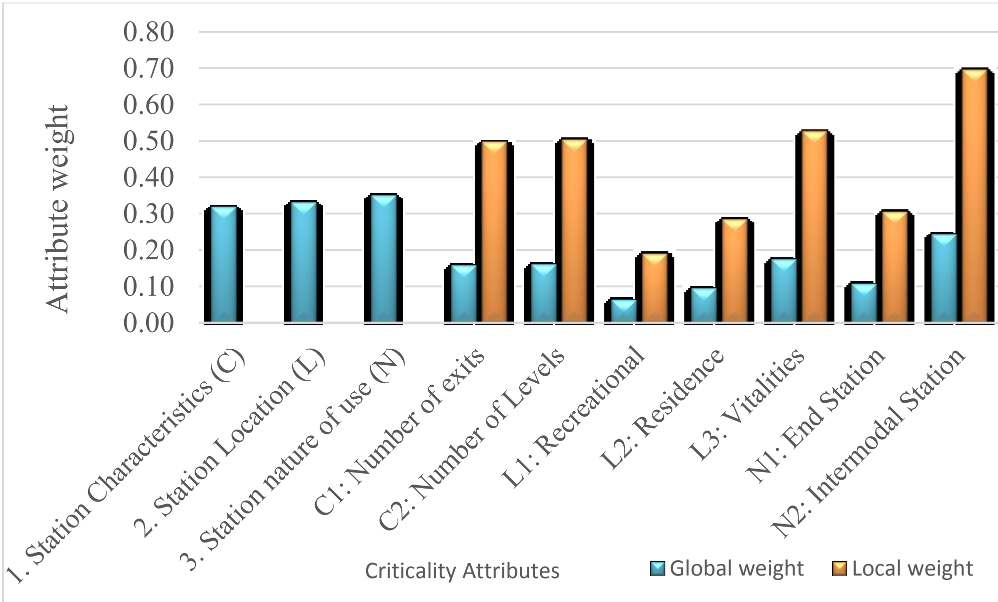


Figure 5.10 Criticality Attributes Local and Global Weights Plot

Model Testing

The Criticality Index model was tested similar to the consequence of failure model. The local and global weights presented in Table 5.14and illustrated graphically in Figure 5.9 and Figure 5.10 were tested using experts opinion. The model was presented to and approved by an STM personnel in charge of the network's risk assessment. He verified the model criteria were actually considered in their decision making process and the output was legitimate and adequately conveys the network studied.

Stations located in a vital location had the second highest global weight of 17.41% followed by the number of levels (16%) and number of lines (15.8%) comprising a subway station. This analysis demonstrates the interdependency between the attributes, none of the station criticality attributes can be measured independently. This highlights the power of the FANP as a calculation method where all the interdependencies are identified and included in the weight calculations. Based on experts' feedback, end stations have lower criticality at (10.67%), whereas stations in residential and recreational locations have the least criticality weights respectively.

Criticality Scores (C_RSi)

Station criticality scores are calculated per station and then normalized for the segment under study. The number of exits in a station is representative of the original station importance and design ridership. It is normalized based on the maximum number of exits per station per network. Number of levels is computed for each station individually starting from the platform level to the station level as identified in the inspection reports, normalization is based upon maximum number of levels per station per network. Station location is a binary value, a station acquires a score of 1 for every attribute it satisfies. Station nature of use attributes are calculated in a similar manner where a station acquires a score of 1 if it is an intermodal or end station and 0 if otherwise.

The total Criticality Index per station (C_R)

Criticality index for all stations in the Montréal subway network (68 stations) are calculated, whereas the index for the six stations in the segment under study are normalized based on the maximum and minimum criticality index per network. Figure 5.11 shows the calculation sheet for the criticality index sub-model. Table 5.15 presents the criticality index calculations for the six stations in the studied segment. Scores are calculated for each station and then normalized with respect to the entire network as shown in the last column.

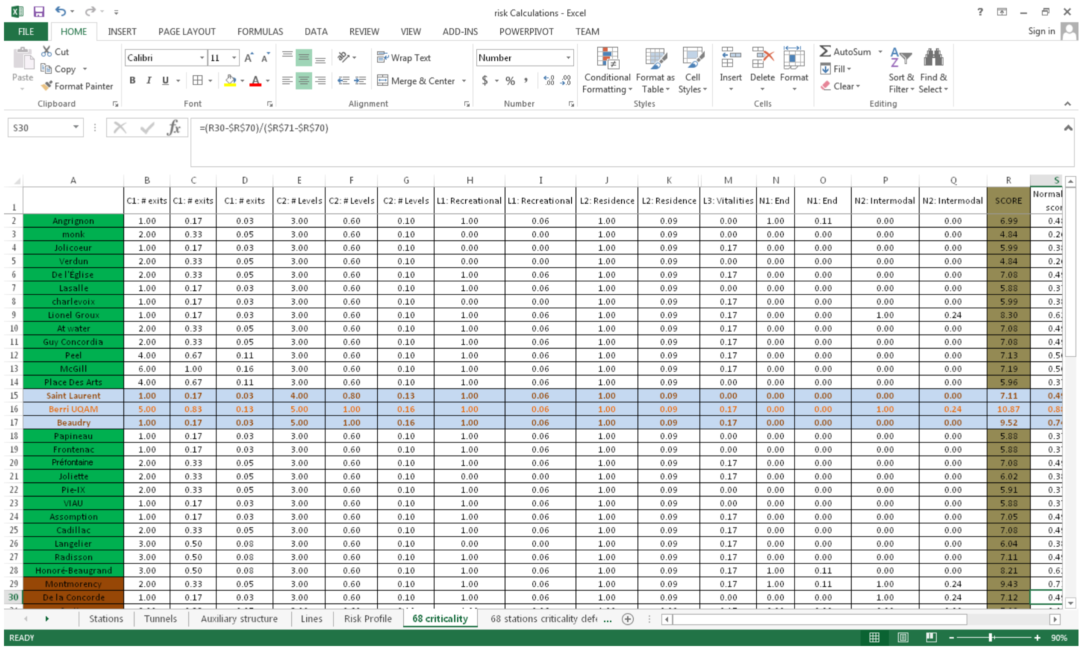


Figure 5.11Screenshot for Criticality Index Calculation Sheet

Table 5.15 Criticality Attributes Calculation

	C1	C2	L1	L2	L3	N1	N2	Score	Normalized score
STA 1	0.05	0.10	0.06	0.09	0.00	0.00	0.00	5.91	0.37
STA 2	0.13	0.16	0.06	0.09	0.17	0.00	0.24	10.87	0.88
STA 3	0.03	0.10	0.06	0.09	0.17	0.00	0.00	7.05	0.49
STA 4	0.03	0.16	0.06	0.09	0.17	0.00	0.00	9.52	0.74
STA 5	0.03	0.13	0.06	0.09	0.00	0.00	0.00	7.11	0.49
STA 6	0.03	0.10	0.06	0.00	0.00	0.00	0.00	4.79	0.25

Calculated criticality indices for different stations indicate STA 2 to be the most critical in the network. This is explained by the fact that STA2 is the only station along the entire network to have three interconnecting lines, accordingly having multiple levels and numerous exits. In addition, STA 2 falls in proximity to the three location criteria of residence, vitalities, and recreational. This is followed by STA 4 having a criticality index of 0.74. STA 4 is the deepest in the entire network having the maximum number of levels and high number of exits. This is reflected in the respectively high criticality index of 0.74. STA 3 and STA 5 have an identical criticality index of 0.49 followed by STA 1 with a criticality index of 0.37 and last, STA 6 with criticality index of 0.25. The Criticality index value was revised and approved by experts.

5.6 FUZZY RULE BASED RISK INDEX MODEL

The probability of failure values and consequence of failure scores aggregated to stations level is combined with the criticality scores in a fuzzy rule based risk index model. MATLAB® fuzzy tool box is used perform the operations using fuzzy membership functions and fuzzy rules extracted from expert feedback. The fuzzy rules presented in Table 4.5 are used to construct a fuzzy expert system capable of assessing the level of risk of any given station. Figure 5.12 illustrates the risk index model configuration on MATLAB. The "Risk system" done by the Mamdani method has three inputs. Probability of failure having five membership functions, consequences of failure having three membership functions, and criticality index having two membership functions. The system operates by means of thirty rules as indicated in the figure and the output of the system is the risk index represented on a scale of five membership functions. Figure 5.13 through Figure 5.16 illustrate the membership functions for the three sub-models and the risk level as identified by experts.

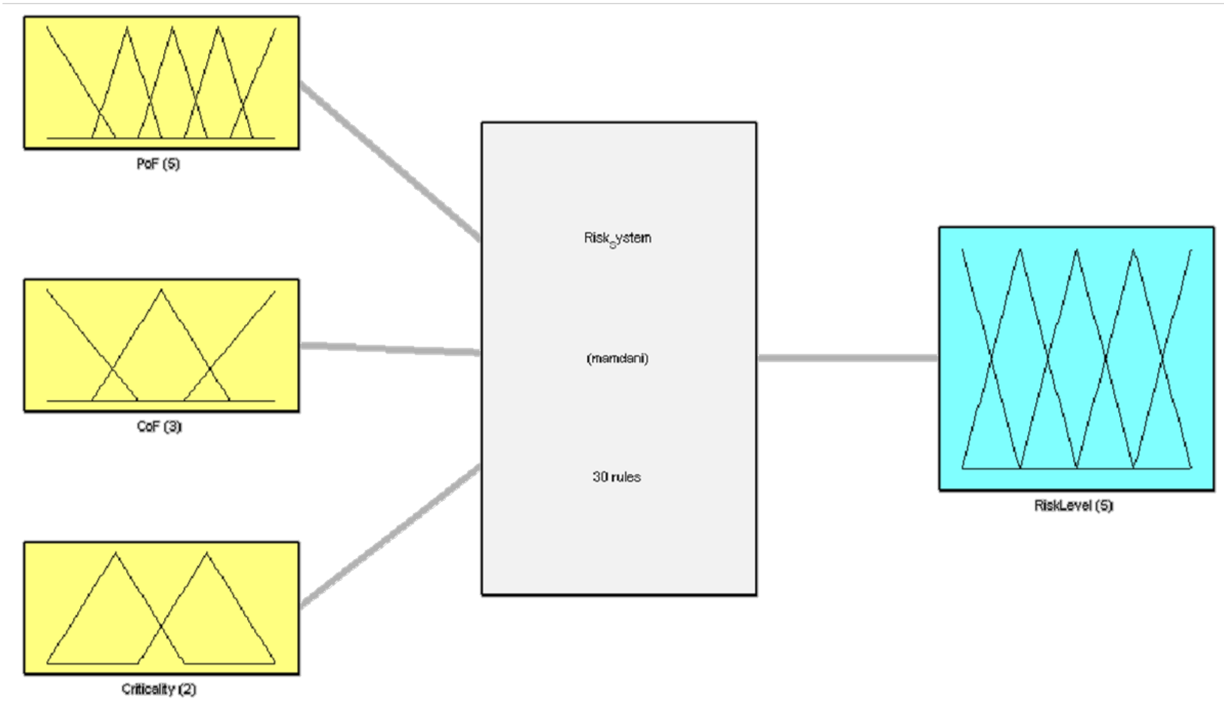


Figure 5.12 Risk Index Model Configuration on MATLAB

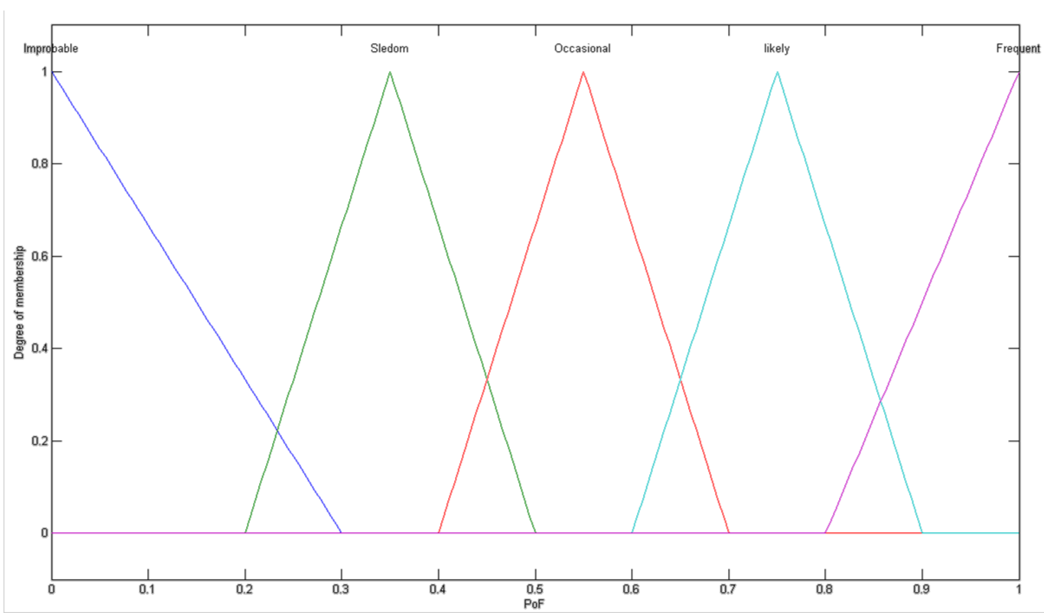


Figure 5.13 Membership Functions for Probability of Failure

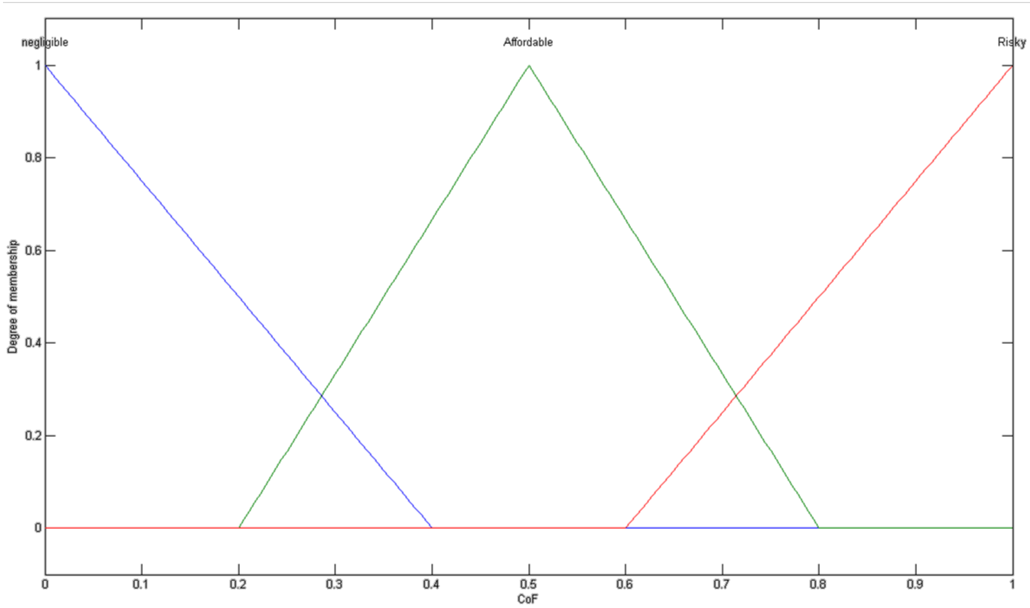


Figure 5.14 Membership Function for Consequence of Failure

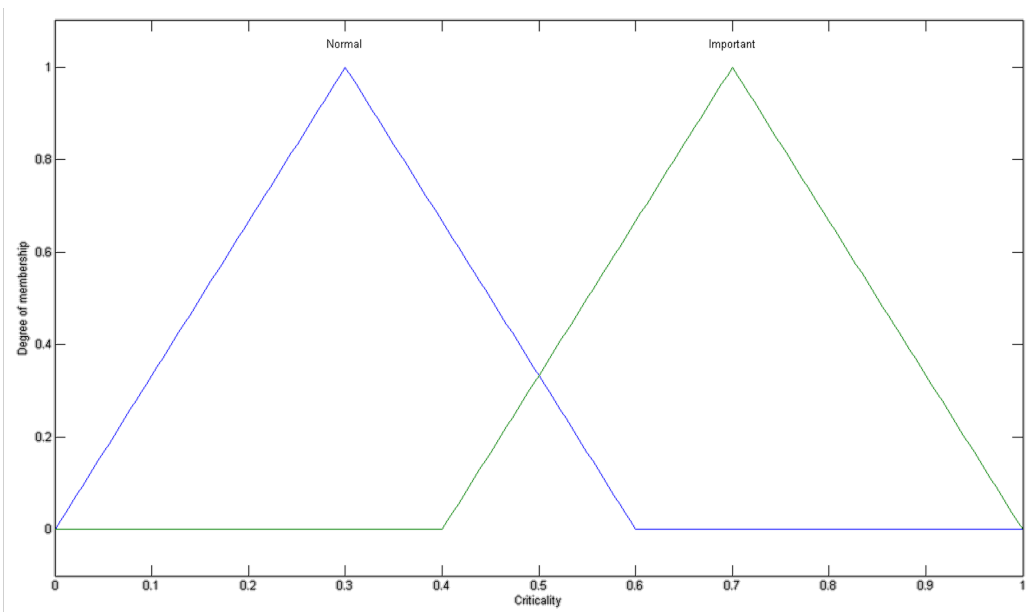


Figure 5.15 Membership Function for Criticality Index

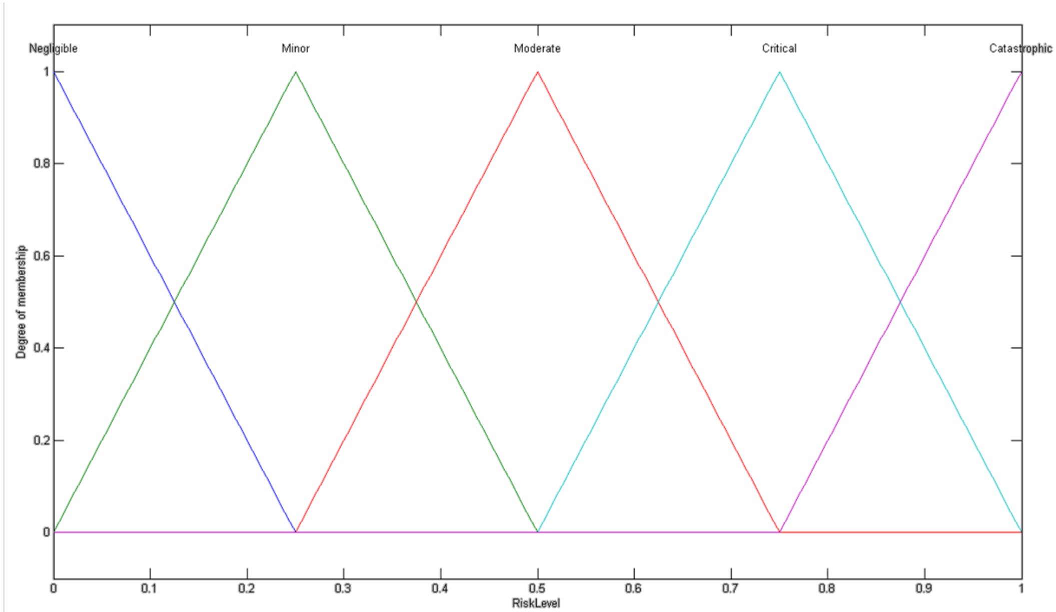


Figure 5.16 Membership Functions for Risk Level

The input variables have a total of ten categories; five for probability of failure, three for consequence of failure and two for criticality index. Therefore thirty rules were entered into the risk mode. Figure 5.17 shows a sample of rule configuration for thr risk index model. The rules to be fired are highlighted in yellow and the resultant risk level is defined in blue. The fuzzy risk model is graphically represented by the fuzzy risk surface shown in Figure 5.18.

Table 5.16 presents the expected risk index for each system.

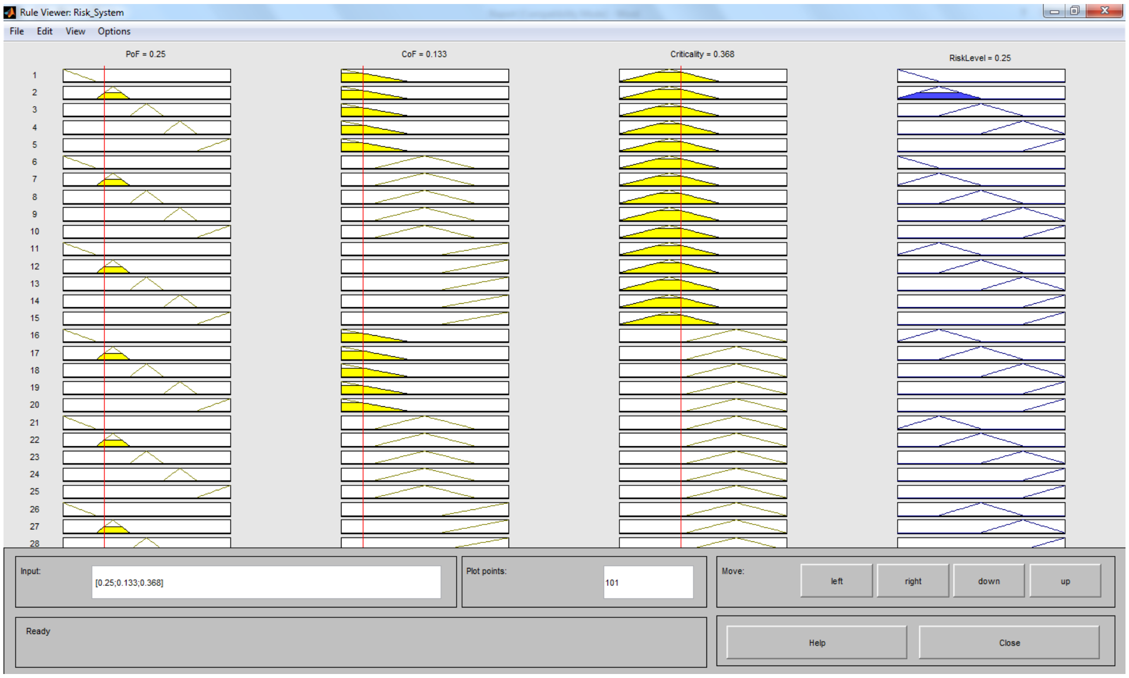


Figure 5.17 Sample Rules configuration for the Risk Index Model

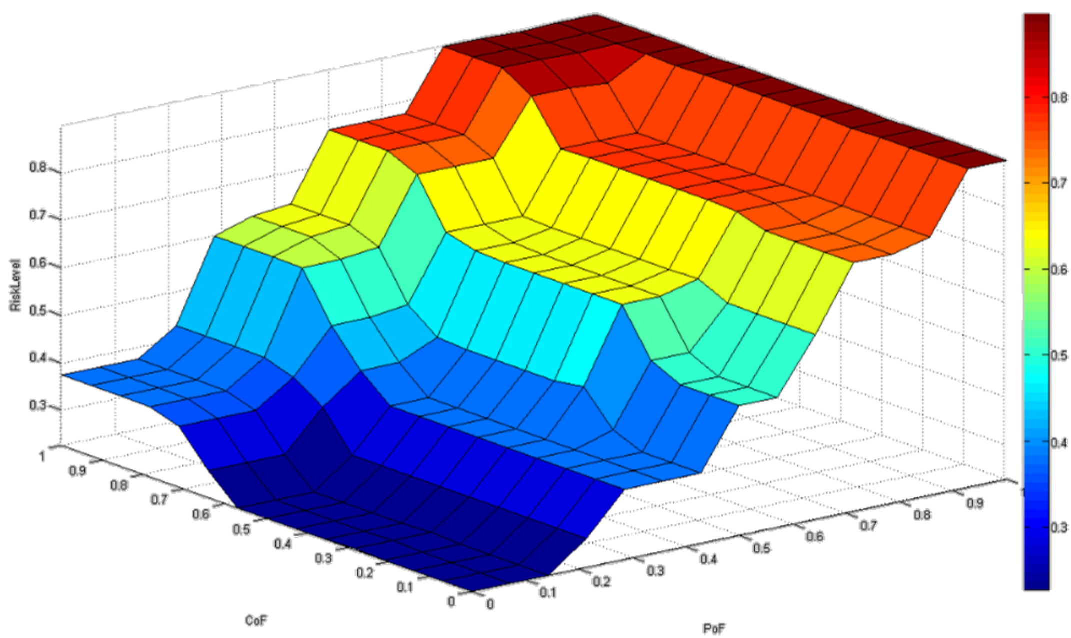


Figure 5.18 Resultant Fuzzy Risk Surface

Table 5.16 Risk Index Calculated Using FRB

Station	Element	PoF	CoF	Criticality Index	Risk Index
STB 1	Station	0.250	0.133	0.368	0.243
	Tunnel	0.117	0.133	0.368	0.0898
	Aux Structure	0.086	0.133	0.368	0.0875
STB2	Station	0.000	0.307	0.883	0.25
	Tunnel	0.180	0.307	0.883	0.25
	Aux Structure	0.000	0.307	0.883	0.25
STB3	Station	0.268	0.093	0.487	0.356
	Tunnel	0.180	0.093	0.487	0.215
	Aux Structure	0.000	0.093	0.487	0.215
STB4	Station	0.673	0.343	0.743	0.821
	Tunnel	0.164	0.083	0.743	0.25
	Aux Structure	0.226	0.083	0.743	0.351
STB5	Station	0.224	0.106	0.493	0.325
	Tunnel	0.149	0.106	0.493	0.221
	Aux Structure	0.000	0.106	0.493	0.221
STB6	Station	0.513	0.279	0.252	0.5
	Tunnel	0.000	0.033	0.252	0.0822
	Aux Structure	0.000	0.033	0.252	0.0822

STA 4 had the highest risk index as expected; this is the combined effect of high probability of failure, consequence of failure, and criticality index as shown. It is noticed that the tunnel and auxiliary structure in the same segment share the same C_R level yet their risk index is very low (0.25 and 0.351) respectively. This is clearly due to the low probability of operational failure of the two systems derived from low PoF and CoF. This resultant risk value is only available through a fuzzy risk model where the criticality index is triggered to action and increases the risk index only in case of high probability of failure and/or consequence of failure. STA 6 comes next with an expected risk index of 0.5. This risk index is mainly affected by the moderately high PoF in spite of low CoF and C_R values. This also is attributed to the fuzzy risk model which triggers the expected risk index value based on an interrelated decision system just like a human expert. The risk index for the remainder elements is considered within acceptable range (0 – 0.35) since they all have low combinations of PoF, CoF and C_R values. The detailed risk report for the two stations is shown in Table 5.17.

Table 5.17 Detailed Risk Report for STA 4 and STA 6

Station Name	STA 4	STA 6
Probability of Operational Failure	0.673	0.513
Consequences of Failure	0.343	0.279
Criticality Index	0.743	0.252
Risk Index	0.821	0.5
Revenue Loss ($CAD)	$583,779	$526,706
Repair Cost ($CAD)	$225,000	$225,000
Service continuation	Weekend interruption	Weekend interruption
Interruption Rate	Total (1)	Total (1)
Time to repair (days)	65	50
User Traffic (annual)	1092714	1281651

STA 4 has a high risk index and thus higher degree of rehabilitation priority, however, actual data regarding STA 4 rehabilitation is not available. STA 6 is currently undergoing rehabilitation actions which conforms to its calculated risk index and PoF values. Rehabilitation actions are scheduled on weekends only to minimize service interruption which confirms the moderate risk index. All model data is used for a detailed report including expected system risk index, monetary consequence of failure defined by revenue loss ($CAD) and repair cost ($CAD). The report also specifies level of service continuation being total, partial or none, the expected time to repair based on the selected rehabilitation strategy, and the user traffic frequency existent per station in case of no interruption at all. In our case study, STA4 and STA6 were the only stations with a triggered rehabilitation action and considerable risk index.

5.7 BUDGET ALLOCATION MODEL

The budget allocation model uses the risk index as the objective function and the M&R actions in as the decision variables to optimize the use of the available annual budget based on the overall risk index and individual risk values exceeding the risk appetite. The risk index is embedded in the fuzzy inference engine, consequently, a multiple regression analysis was run on the fuzzy model. All different logical combinations of PoF, CoF and C_R index values, comprising a total of 40 data points, were entered into the regression model using MS Excel® . Sample of random data entry values are shown in Table 5.18. This serves to validate the model through providing a concrete equation; on the other hand, the resultant equation will be used in the budget allocation model as the objective function.

Table 5.18 Sample Random Data Entry into Risk Model

PoF	*CoF*	*Cr*	*Risk Index*
0.1	0.1	0.1	0.0876
0.2	0.2	0.2	0.103
0.3	0.3	0.3	0.25
0.4	0.4	0.4	0.25
0.5	0.5	0.5	0.625
0.6	0.6	0.6	0.75
0.7	0.7	0.7	0.897
0.8	0.8	0.8	0.905
0.9	0.9	0.9	0.905
1	1	1	0.92
1	0.1	0.1	0.915
0.9	0.2	0.2	0.905
0.8	0.3	0.3	0.75
0.7	0.4	0.4	0.75
0.6	0.5	0.5	0.625
0.5	0.6	0.6	0.75
0.4	0.7	0.7	0.607
0.3	0.8	0.8	0.75
0.2	0.9	0.9	0.5
0.1	1	1	0.5

For a total of 40 observations, R^2 value equals to 0.85, whereas, the adjusted R^2 (taking in consideration sample size) equals to 0.84. Regression statistics are shown in Table 5.19. The resultant risk equation can be seen in equation (5.1) at an intercept of 0.005, Probability of failure, consequence of failure, and criticality index has the values of 0.793, 0.168, and 0.182 respectively.

$$\textit{Risk Index} = 0.005+0.793\ PoF + 0.168\ CoF + 0.183\ C_R \tag{5.1}$$

Table 5.19 Regression Statistics

Multiple R	0.924
R^2	0.854
Adjusted R^2	0.842
Standard Error	0.103
Observations	40

Predicted risk values versus actual risk values are plotted in Figure 5.19. From the plot, it is visible that the two curves are relatively close which further validates the risk index model and facilitates further calculations.

The extent of Maintenance and Rehabilitation (M&R) actions differ greatly depending upon the state of the component under assessment. The action taken could be the simplest and cheapest like preventive maintenance or the case might require the other extreme of element replacement, which would be the most expensive and complicated option. The network level assessment requires the action be selected with a higher level than the component level.

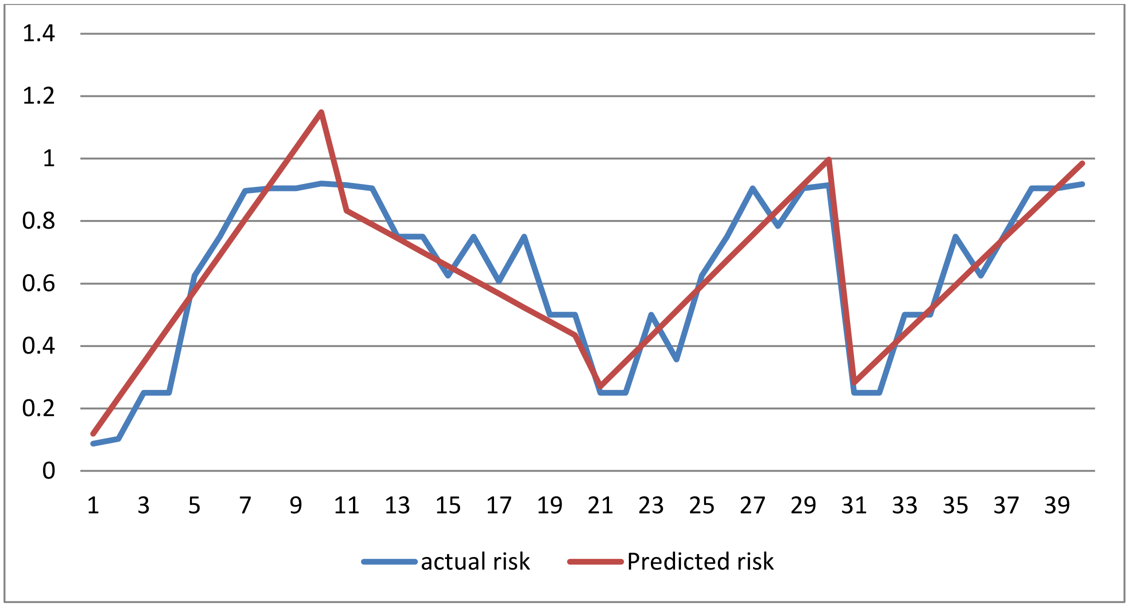


Figure 5.19 Predicted Risk versus Actual Risk Plot

Table 5.8 includes five generic M&R actions for our case study. This data is deducted from literature review (Farran 2006) and inspection reports. Action 5 is a full element replacement which requires a full service disruption, consequently, a total station and service interruption (loss of revenue) is expected. Action 4 is repairing the most defective parts while maintain the rest of the structure. This option is usually undertaken with minimizing the service disruption in consideration, accordingly, M&R work is done during weekends only as the current case of the yellow line in the Montreal subway. The different indirect costs including; costs for weekend shifts, overtime, and pre-elongated construction period due to the restricted work schedule are considered in the provided cost.

For the purpose of the case study, maximum allowable risk index of 0.6 is set and accordingly, the budget allocation equation will take the form seen in equations (5.2) and (5.3). The weights are assumed to be equal to 0.5 and the maximum allowable annual budget at $1,000,000.

The optimization objectives are;

$$Min\ f(x) = RI * w_1 + RI_{0.6} * w_2 \tag{5.2}$$

$$Min \sum_{i=1}^{N} \sum_{j=1}^{J} C_{ij} \tag{5.3}$$

Subject to the following constraint;

$$\sum_{i=1}^{N} \sum_{j=1}^{J} C_{ij} \leq 1000000 \tag{5.4}$$

Figure 5.20 illustrates the model identification process where the upper and lower bound for each chromosome is identified, these are the range of possible rehabilitation actions assigned the number 1 for no action to 5 for total element rehabilitation. The multiple-objective model is formulated using the SolveXL add-in in MS Excel® workbook as seen in Figure 5.21. The model uses GA to solve the multiple objective problems at hand.

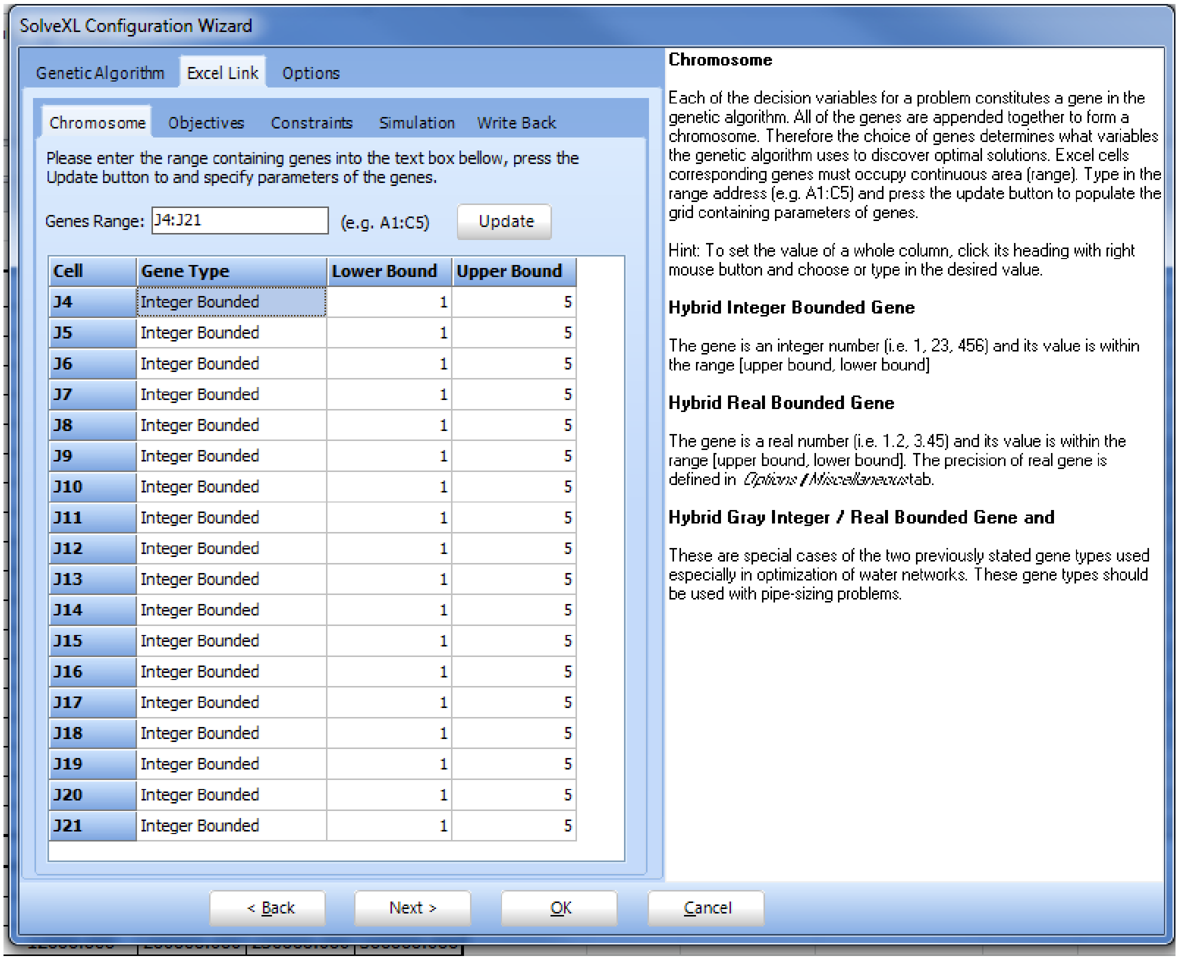
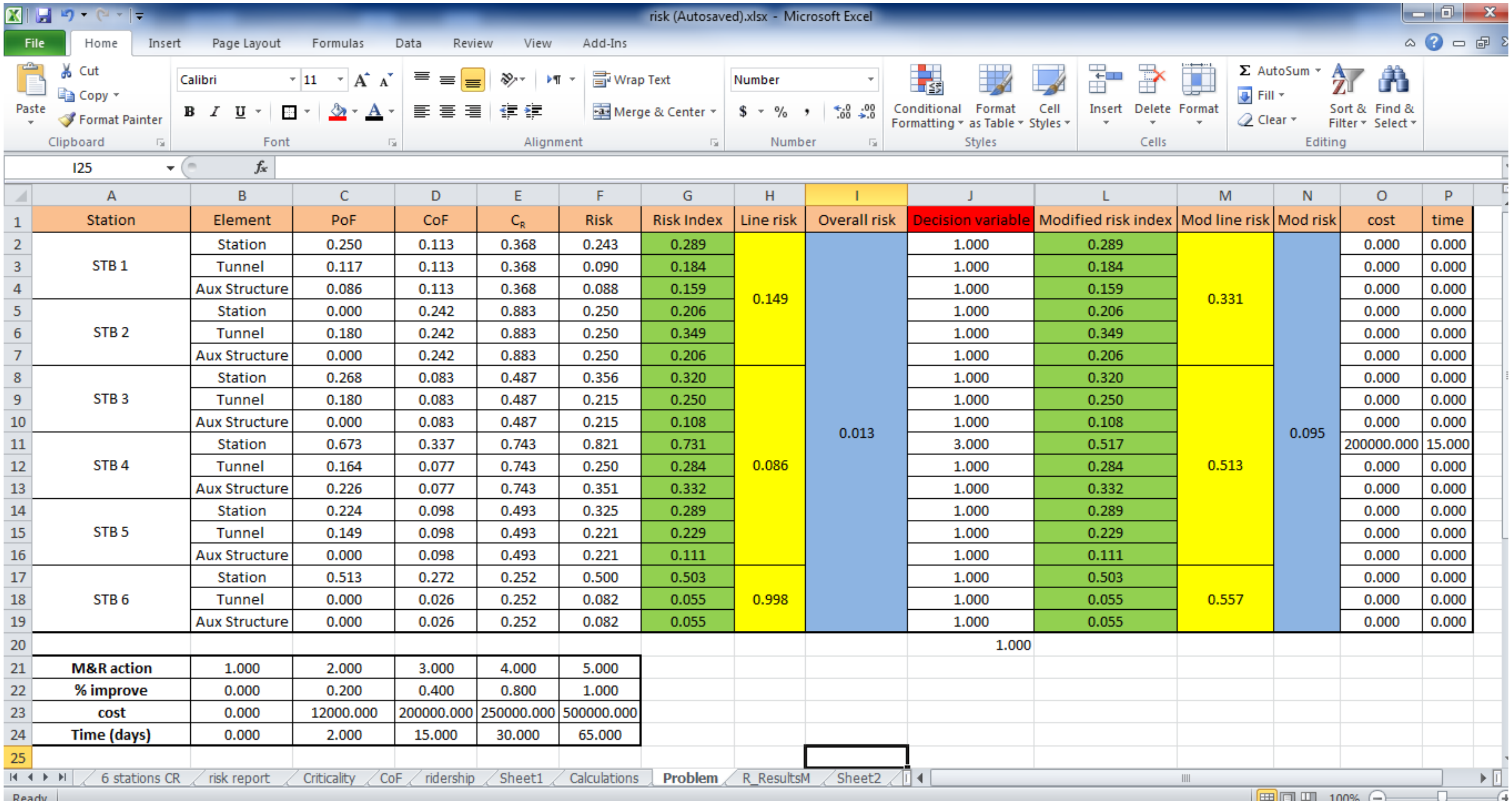


Figure 5.20 Budget Allocation Model Identification



	A	B	C	D	E	F	G	H	I	J	L	M	N	O	P
1	Station	Element	PoF	CoF	C_R	Risk	Risk Index	Line risk	Overall risk	Decision variable	Modified risk index	Mod line risk	Mod risk	cost	time
2	STB 1	Station	0.250	0.113	0.368	0.243	0.289	0.149	0.013	1.000	0.289	0.331	0.095	0.000	0.000
3		Tunnel	0.117	0.113	0.368	0.090	0.184			1.000	0.184			0.000	0.000
4		Aux Structure	0.086	0.113	0.368	0.088	0.159			1.000	0.159			0.000	0.000
5	STB 2	Station	0.000	0.242	0.883	0.250	0.206			1.000	0.206			0.000	0.000
6		Tunnel	0.180	0.242	0.883	0.250	0.349			1.000	0.349			0.000	0.000
7		Aux Structure	0.000	0.242	0.883	0.250	0.206			1.000	0.206			0.000	0.000
8	STB 3	Station	0.268	0.083	0.487	0.356	0.320	0.086		1.000	0.320	0.513		0.000	0.000
9		Tunnel	0.180	0.083	0.487	0.215	0.250			1.000	0.250			0.000	0.000
10		Aux Structure	0.000	0.083	0.487	0.215	0.108			1.000	0.108			0.000	0.000
11	STB 4	Station	0.673	0.337	0.743	0.821	0.731			3.000	0.517			200000.000	15.000
12		Tunnel	0.164	0.077	0.743	0.250	0.284			1.000	0.284			0.000	0.000
13		Aux Structure	0.226	0.077	0.743	0.351	0.332			1.000	0.332			0.000	0.000
14	STB 5	Station	0.224	0.098	0.493	0.325	0.289			1.000	0.289			0.000	0.000
15		Tunnel	0.149	0.098	0.493	0.221	0.229			1.000	0.229			0.000	0.000
16		Aux Structure	0.000	0.098	0.493	0.221	0.111			1.000	0.111			0.000	0.000
17	STB 6	Station	0.513	0.272	0.252	0.500	0.503	0.998		1.000	0.503	0.557		0.000	0.000
18		Tunnel	0.000	0.026	0.252	0.082	0.055			1.000	0.055			0.000	0.000
19		Aux Structure	0.000	0.026	0.252	0.082	0.055			1.000	0.055			0.000	0.000
20										1.000					
21	M&R action	1.000	2.000	3.000	4.000	5.000									
22	% improve	0.000	0.200	0.400	0.800	1.000									
23	cost	0.000	12000.000	200000.000	250000.000	500000.000									
24	Time (days)	0.000	2.000	15.000	30.000	65.000									

Figure 5.21 Budget Allocation Model Calculation Sheet

Figure 5.22 demonstrates the process of defining the Pareto optimal surface for different combinations of rehabilitation actions under condition of the stated budget.

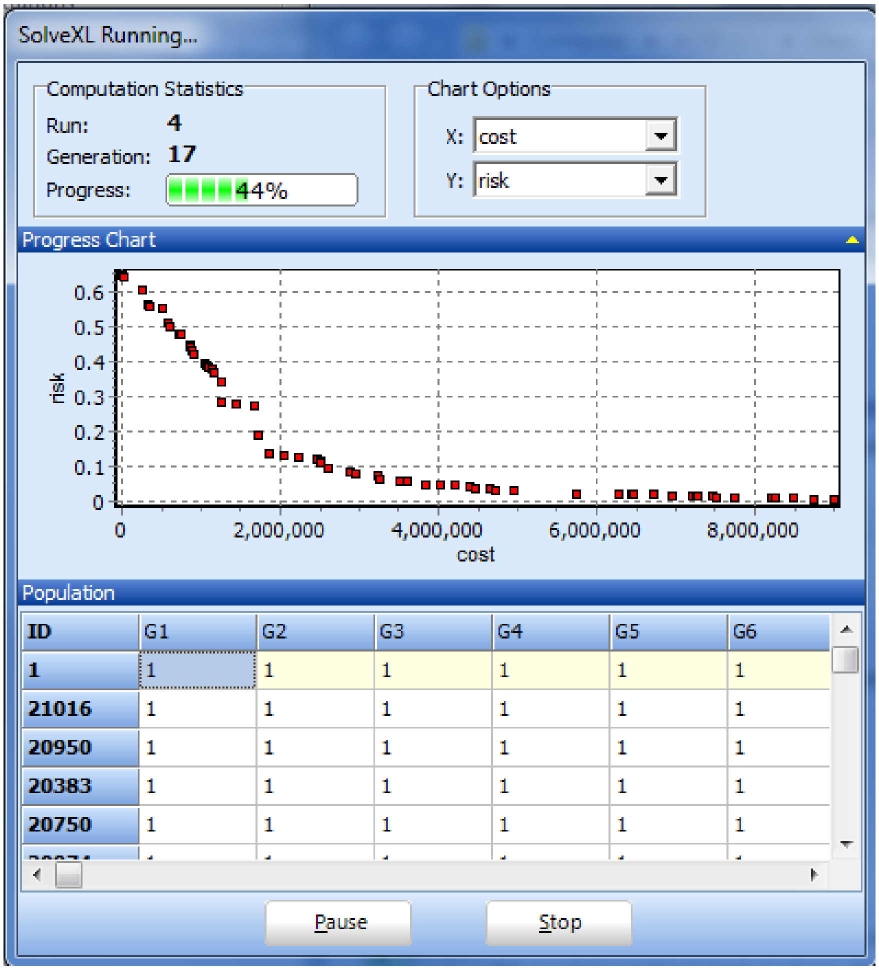


Figure 5.22 Budget Allocation Model Running

The risk index for the segment under study and the individual systems are all under the threshold of 0.6 except for STA 4, where a calculated risk index of 0.731 exists. Since the model aims at minimizing the overall risk at the least available cost, the output of the segment optimization was selecting the third rehabilitation action, minor rehabilitations, as the most appropriate, thus decreasing the risk index of STR 4 to 0.517 and the overall risk index from 0.013 to an overall risk index of zero.

5.8 DISCUSSION

Each time a budget decision is taken to renovate an element and spend a specific amount of budget, risk assessment is informally utilized. Unfortunately, this process is poorly documented in the subway asset management domain. In addition, the process is mostly subjective based on the decision maker and lacks the structure and consistency of a decision making tool. This is the main gap this research targeted addressing. However, it is important to realize what this model can and cannot do; therefore some important notes are highlighted in the following paragraphs.

1. The framework adopts an intelligent simplification approach. The subway framework was simplified enough to balance between a comprehensive model covering the most vital risk aspects while maintaining a simple and easy to implement model. As per experts' comments, the main cause of a lack of a decision making tool is the vast level of complexity, therefore this model is developed to be comprehensive yet easy to comprehend.

2. The probability of failure sub-model addresses the loss of integrity of an element indicating the element failed to successfully perform its intended function and no more meets its delivery requirements, hence, operational failure. This failure indicates loss of reliability of the targeted component.

3. The indexed versus the monetary consequences of failure have long been in comparison. This research conducted the consequences of failure model using the indexed approach. While monetary consequences of failure are easy to calculate for financial and operational impacts of failure, the case is different for social impacts of failure. Monetizing social impacts requires translating the different attributes to their dollar

values. Due to lack of historical operational failure data, a valid data base was not available to adequately quantify different consequences of failure attributes. The other route is using experts' knowledge; this can only be done with the complete cooperation and help of multi-discipline and multi-sector experts which was not possible in this research. However, an indexed model has its own advantages; it allows for incorporating incomplete knowledge and updating the model when new data emerges and this allows including a wider spectrum of information. According to (Muhlbauer, 2004), indexed models are especially useful when there is need to consider multiple factors simultaneously where complete knowledge is unavailable. In addition, even if quantification of risk factors is imperfect; results are usually able to portray a reliable picture of elements where risk is relatively lower or higher.

4. The scalability of this model should be addressed as well. This framework is a starting point for best practices for subway networks. However, applying this model on a full scale requires working in conjunction with different departments in a subway network authority to ensure all the possible information is adequately captured and considered in the model. This model should continuously evolve as new data or attributes emerge.

CHAPTER 6. CONCLUSION AND RECOMMENDATIONS

6.1 CONCLUSION

The research beforehand presents a compiled effort to develop a network level risk assessment scheme for subway networks. Studying models developed in academia so far and those implemented by subway authorities revealed a number of gaps. First, none of the models studied networks from a functional point of view nor there is any documented effort to analyze risk level on an element or station level. Second, only two of the available models studied the subway from a network perspective rather than an asset perspective. Last, a risk-based budget allocation methodology cannot be found in academia or practices. This triggered the current research to develop a chain of sub-models and models aiming at clarifying the risk assessment procedure for subway networks on asset and network levels. The current practice adopted for selecting stations for rehabilitation is considered a black box where no specific algorithm can be identified. This disadvantage is the main advantage of the current model.

A generic subway hierarchy is proposed and risk is assessed through measuring probability of failure, consequence of failure and functional importance of subway stations and integrated to the network level. Probability of failure is predicted using reliability-based Weibull function and inspection report for different structural elements. Aggregation to network level is done using parallel-series network technique. Seven criteria are used to assess consequence of failure along financial, social, and, operational perspectives. A criticality index is introduced to the classical risk equation to assess the functional importance a station plays in its location. Criticality is assessed using seven attributes along three main criteria. Integration of risk equation components is done using the fuzzy inference engine to ensure incorporating the experts knowledge into the decision making process. Relative weights of consequence of failure and criticality models attributes is calculated using experts feedback provided through a survey and the fuzzy analytical network process. With regards to consequence of failure sub-model, social impacts had the highest relative weight of 38% followed by operational and financial impacts at 34% and 27.65% respectively. Within the consequence of failure attributes, time to repair had the highest global impact of 18.45% followed by ease of providing alternative and user traffic frequency at 15.69% and 15% respectively. Revenue loss at 14.96% was followed closely by service continuation (12.95%) and replacement/repair cost (12.68%), whereas, the interruption rate came last at a global weight of 10.22%. Assessing a subway station criticality revealed station location to have the highest weight of 35% with stations in vital location being the most important with local weight of 52.55% followed by stations in residence locations (28.45%) and last, stations in recreational locations (19%). Station nature of use as being end or intermodal was the second highest weight of 33% where intermodal station had higher local weight of 69.5% with respect to end stations with a weight of 30.5%. Station characteristics came last with overall weight of 31.82%, the two attributes within station characteristics came close with local weights of 49.7% and 50.3% for number of levels and number of exits respectively.

Experts were asked to provide the relations by which probability of failure, consequence of failure, and criticality indices can be integrated to construct a risk index model that can be used to prioritize stations based on risk level. This resulted in a total of 30 rules that were entered into the fuzzy model and used to develop relations and finally construct a risk surface. The developed model was used on an actual case study in Montreal subway of six stations along three interconnected lines. The model ranked two stations as having the highest risk index and accordingly the highest rehabilitation priority. The results are validated through the current rehabilitation actions undergoing the station ranked with a high risk index. The fuzzy risk index model used provides a numerical representation for the risk level which better represents the case and facilitates the analysis. Risk model components are used as the objective function together with five generic rehabilitation actions associated with their cost, time, and percentage improvement as the decision variables in a risk-based budget allocation model. The model is run using the current data from the station under rehabilitation and aims at selecting the optimum rehabilitation strategy based on the available fund, network wide risk level, and the decision maker risk appetite. The proposed model is comprehensive since it assesses risk with its components on asset and network levels yet, it is easy to implement and understand. The model is believed to help public authorities assess different elements in a network and take an educated decision of their rehabilitation priority.

6.2 RESEARCH CONTRIBUTIONS

The developed risk model is deemed comprehensive and is expected to provide a strategic perspective for the state and condition of the subway networks. The methodology proposed covers different aspects for the assessment of subway networks from a risk-wise perspective. The achieved contributions are outlined as follows;

- Model probability of failure based on structural reliability curves developed through inspection reports and experts feedback,
- Develop a multi-perspective consequence of failure model along financial, social, and operational failure impacts,
- Propose and develop a system criticality model. The model analyzes stations in terms of their respective importance to the customers and the service delivered,

- Integrate the three sub-models into a fuzzy-based risk index model while incorporating actual expert knowledge used to take the rehabilitation decision,
- Develop a risk-based budget allocation model to maximize the use of the available budget and minimize the overall expected risk of failure.

6.3 RESEARCH LIMITATIONS

The current research presents a novel framework for assessing risk index on asset and network levels in subway. Then it proceeds to prioritize stations for rehabilitation using a multiple objective optimization model. However, some limitations to the model are noted, most of which are pertinent to the data scarcity problem;

- Experts' feedback regarding the risk assessment process in subway network should be formally investigated on a wider scale and in a more sophisticated manner,
- The weights of consequence of failure and criticality models attributes require more expert feedback to be verified. Moreover, the weights should be validated by a team of designated experts assigned to the project,
- The proposed framework should be validated using a larger data set with more precise information. A wider data set means more variability,
- The rehabilitation actions assumed in the model are all generic. Actual rehabilitation strategies performed and the detail of each strategy with add depth and preciseness to the model,

- Real life data is required to validate the budget allocation model. This will include a range of actual rehabilitation actions, associated cost, required time to repair and the service interruption,
- The model addresses operational failure derived from failure in structural systems only. A more comprehensive approach is studying the other systems and integrating them into the framework.

6.4 RECOMMENDATION AND FUTURE WORK

The proposed model, however comprehensive, yet some recommendations and potential future work is presented in the following section to better enhance the model and increase its reliability. This is presented on twofold, current study enhancement areas and current study extension area for future work in the topic. These recommendations are summarized below;

Current Study enhancement area;

- Failure of other systems like mechanical, electrical, and security and communication should be integrated into the probability of failure model for a more comprehensive failure analysis,
- Once other systems are considered, the interdependency and importance between systems should be investigated and considered in the analysis,
- More data collection is required in terms of quantity and methodology. More replies to the proposed questionnaire are required to statistically increase the reliability of the computed attributes,

- Other data collection methodologies can be applied to enhance the current research such as holding workshops to identify actual best practices used to select stations for rehabilitation.
- Consulting multi-discipline and multi-sector experts to deliver reliable feedback at different stages of the research,
- Collecting actual data for M&R actions used in subway networks, this can be done through consulting actual rehabilitation reports and by conducting structured/unstructured interviews with rehabilitation engineers.
- Develop a web-based software tool to make the model available for public authorities use and collect data for better model enhancement accordingly.

Current Study extension areas

- Incorporating failure of other systems into the model further than the structural systems failure, referring to the proposed subway hierarchy, this might include mechanical, electrical, and security and communication systems.
- Addressing different categories of risk of failure including events external and internal to the organization. Events external to the organization include naturally occurring events, external impacts and, external aggression.
- Using the developed risk index to conduct a benefit cost analysis for short and long term asset management. A formal benefit cost analysis can be used as a base for prioritization.

- The probability of failure sub-model is mainly based on visual inspection reports. Further research in this area is required to compute probability of failure based on other methods such as non-destructive techniques.

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APPENDIX A

QUESTIONNAIRE

An Integrated Risk-based Asset Management Tools for Subway Systems

SECTION I: GENERAL INFORMATION

Page description:
This survey is conducted as a part of an ongoing research for a PhD thesis at Concordia University under the title of: An Integrated Risk-based Asset Management Tools for Subway Systems. The purpose of this research is to analyze the impacts of failure expected from subway elements failure (Section II) and subway stations importance with respect to each other (Section III) in an effort to rank stations for rehabilitation accordingly.

The survey completion time is approximately 10 minutes. Thank you in advance for your co-operation and participation in this research, your feedback is highly appreciated. The information Collected from the questionnaire will be used for academic research only and is highly confidential. All the respondent information will be kept anonymous.

Please indicate the name of your company

Name:

Position: *

Years of experience: *

Would you like the name of your company be stated and acknowledged in this research? *

- ○ Yes
- ○ No
- ○ Other [ ]

This survey estimates the relative importance of the expected consequences of failure and subway stations criticality to be further used for risk assessment. The comparison between factors will be conducted using a pairwise comparison matrix and a scale that expresses the qualitative judgments between criteria numerically. The scale indicates the relative importance through answering the question; "Given a control criterion (Z) which of the two criteria (X) and (Y) is more dominant with respect to (Z) criterion?" Kindly indicate your preference through selecting the number that best represents your point of view. The following table illustrates an example.

Example:

In the table below, consider comparing ***"Social Impacts"*** (Criterion X) with ***"Financial Impacts"*** (Criterion Y) with respect to "***Consequences of failure***".

With respect to Z "Consequences of failure"										
Indicate the relative importance of (X) on (Y) or vice versa										
(X)	Absolute	Very Strong	Strong	Moderate	Equal	Moderate	Strong	Very Strong	Absolute	**(Y)**
Social Impacts	(9)	(7)	(5)	(3)	(1)	(3)	(5)	(7)	(9)	Financial Impacts
	(9)	(7)	(5)	(3)	(1)	(3)	(5)	(7)	(9)	Operational Impacts

*If you consider that "Social Impacts" is more important than "Financial Impacts" and the degree of importance is **"Strong"** then circle the number (5)*

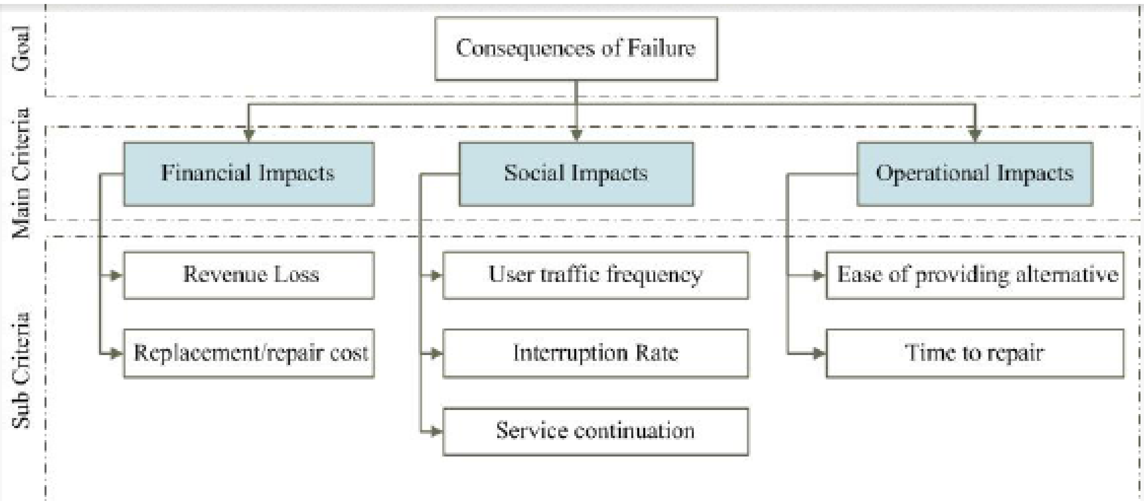
If you consider that "Social Impacts" is equally important to "Financial Impacts" then circle the number (1)

*If you consider that "Financial Impacts" is more important than "Social Impacts" and the degree of importance is **"Absolute"** then circle the number (9)*

*The same procedure is then followed when comparing **"Social Impacts"** with **"Operational Impacts"**.*

SECTION II: CONSEQUENCES OF FAILURE

Page description:
The expected consequences of failure were identified and clustered as shown in the following figure. Please review the factors and fill in the following comparison matrices.



Kindly indicate your preference of importance of different impacts of failure by selecting the appropriate number that reflects your point of view;

A. Main criteria comparison with respect to goal " Consequences of failure" ;

1. With respect to "Consequences of failure", Indicate the relative importance of impacts over eachother *

	9 Absolute (L)	7 Very strong(L)	5 Strong(L)	3 Moderate(L)	1 Equal	3 Moderate	5 Strong	7 Very strong	9 Absolute
Social Impacts	○	○	○	○	○	○	○	○	○

2. With respect to "Consequences of failure", Indicate the relative importance of impacts over eachother *

	9 Absolute(L)	7 Very strong(L)	5 Strong(L)	3 Moderate(L)	1 Equal	3 Moderate	5 Strong	7 Very strong	9 Absolu
Social Impacts	○	○	○	○	○	○	○	○	○

B. Main criteria comparison with respect to each other ;

3. With respect to "Financial Impacts", Indicate the relative importance of impacts over eachother *

	9 Absolute(L)	7 Very strong(L)	5 Strong(L)	3 Moderate(L)	1 Equal	3 Moderate	5 Strong	7 Very strong	9 Absolu
Social Impacts	○	○	○	○	○	○	○	○	○

4. With respect to "Social Impacts", Indicate the relative importance of impacts over eachother *

	9 Absolute(L)	7 Very strong(L)	5 Strong(L)	3 Moderate(L)	1 Equal	3 Moderate	5 Strong	7 Very strong	9 Absol
Financial Impacts	○	○	○	○	○	○	○	○	○

5. With respect to "Operational Impacts", Indicate the relative importance of impacts over eachother *

	9 Absolute(L)	7 Very strong(L)	5 Strong(L)	3 Moderate(L)	1 Equal	3 Moderate	5 Strong	7 Very strong	9 Absol
Financial Impacts	○	○	○	○	○	○	○	○	○

C. Sub-criteria comparison with respect to main criteria;

6. With respect to "Financial Impacts of failure", Indicate the relative importance of impacts over eachother *

	9 Absolute(L)	7 Very strong(L)	5 Strong(L)	3 Moderate(L)	1 Equal	3 Moderate	5 Strong	7 Very strong	9 Absolu
Loss of revenue	○	○	○	○	○	○	○	○	○

7. With respect to "Social Impacts of failure", Indicate the relative importance of impacts over eachother *

	9	7 Very	5	3	1	3	5	7 Very

	Absolute(L)	strong(L)	Strong(L)	Moderate(L)	Equal	Moderate	Strong	strong	Al
Service continuation	○	○	○	○	○	○	○	○	

8. With respect to "Social Impacts of failure", Indicate the relative importance of impacts over eachother *

	9 Absolute(L)	7 Very strong(L)	5 Strong(L)	3 Moderate(L)	1 Equal	3 Moderate	5 Strong	7 Very strong	Al
Service continuation	○	○	○	○	○	○	○	○	

9. With respect to "Operational Impacts of failure", Indicate the relative importance of impacts over eachother *

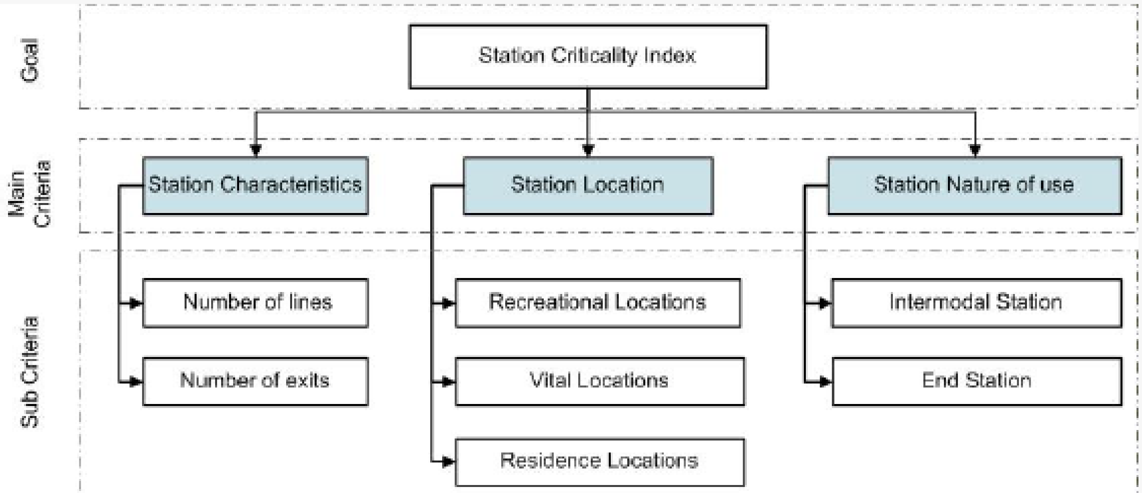
	9 Absolute(L)	7 Very strong(L)	5 Strong(L)	3 Moderate(L)	1 Equal	3 Moderate	5 Strong	7 Very strong	9 Absolute
Time to repair	○	○	○	○	○	○	○	○	○

10. Are there any other impacts of failure that the survey failed to address? If yes, please indicate them.

11. Based on your experience, what is the maximum allowable number of service interruptions per year to sustain a good service reputation? *

SECTION III: STATION CRITICALITY

Page description:
This section attempts to measure the relative criticality of subway stations. Based on the literature review and case studies, the factors contributing to station criticality were identified as illustrated in the following figure.



A. Main criteria comparison with respect to goal " Station Criticality" ;

12. With respect to "Station Criticality", Indicate the relative importance of impacts over eachother *

	9 Absolute(L)	7 Very strong(L)	5 Strong(L)	3 Moderate(L)	1 Equal	3 Moderate	5 Strong	7 Very strong
Station Characteristics	○	○	○	○	○	○	○	○

13. With respect to "Station Criticality", Indicate the relative importance of impacts over eachother *

	9	7 Very	5	3	1	3	5	7 Very

	Absolute(L)	strong(L)	Strong(L)	Moderate(L)	Equal	Moderate	Strong	strong
Station Characteristics	○	○	○	○	○	○	○	○

B. Main criteria comparison with respect to each other ;

14. With respect to "Station Characteristics", Indicate the relative importance of impacts over eachother *

	9 Absolute(L)	7 Very strong(L)	5 Strong(L)	3 Moderate(L)	1 Equal	3 Moderate	5 Strong	7 Very strong	9 Absol
Station Location	○	○	○	○	○	○	○	○	○

15. With respect to "Station Location", Indicate the relative importance of impacts over eachother *

	9 Absolute(L)	7 Very strong(L)	5 Strong(L)	3 Moderate(L)	1 Equal	3 Moderate	5 Strong	7 Very strong	9 Absolut
Station Size	○	○	○	○	○	○	○	○	○

16. With respect to "Station Nature of use", Indicate the relative importance of impacts over eachother *

	9 Absolute(L)	7 Very strong(L)	5 Strong(L)	3 Moderate(L)	1 Equal	3 Moderate	5 Strong	7 Very strong
Station Characteristics	○	○	○	○	○	○	○	○

C. Sub-criteria comparison with respect to main criteria;

17. With respect to "Station Characteristics", Indicate the relative importance of impacts over eachother *

	9 Absolute(L)	7 Very strong(L)	5 Strong(L)	3 Moderate(L)	1 Equal	3 Moderate	5 Strong	7 Very strong	9 Absolu
Number of exits	○	○	○	○	○	○	○	○	○

Recreational locations refer to locations of main touristic attractions, ;locations of sports, culture, or, transportation. Vital locations refer to locations of worship, business, educational, governmental, or, health care. Residence locations refer to locations of high, medium or low residence.

18. With respect to "Station Location", Indicate the relative importance of impacts over eachother *

	9 Absolute(L)	7 Very strong(L)	5 Strong(L)	3 Moderate(L)	1 Equal	3 Moderate	5 Strong	7 Very strong	Al
Recreational area	○	○	○	○	○	○	○	○	

19. With respect to "Station Location", Indicate the relative importance of impacts over eachother *

	9 Absolute(L)	7 Very strong(L)	5 Strong(L)	3 Moderate(L)	1 Equal	3 Moderate	5 Strong	7 Very strong	Al
Recreational area	○	○	○	○	○	○	○	○	

20. With respect to "Station Nature of use", Indicate the relative importance of impacts over eachother *

	9 Absolute(L)	7 Very strong(L)	5 Strong(L)	3 Moderate(L)	1 Equal	3 Moderate	5 Strong	7 Very strong	9 Absolut
End Station	○	○	○	○	○	○	○	○	○

21. Are there any other factors of station criticality that the survey failed to address? If yes, please indicate them.

Thank you !

Thank you for taking our survey. Your response is very important to us. If you would like any further information, please feel free to contact me via email monabuhamd@yahoo.com

SAMPLE E-MAIL FILLED QUESTIONNAIRES

Concordia

Questionnaire Survey

SECTION I: GENERAL INFORMATION

Thank you for taking part in this questionnaire; your effort and time are highly appreciated.

This questionnaire is conducted as a part of an ongoing research for a PhD thesis at Concordia University under the title of: An Integrated Risk-based Asset Management Tools for Subway Systems. The purpose of this research is to analyze the impacts of failure expected from subway elements failure (Section II) and subway stations importance with respect to each other (Section III).
The information Collected from the questionnaire will be used for academic research only and is highly confidential. All the respondent information will be kept anonymous.

Please indicate the name of your company; ..... [redacted] ....

Name:	[redacted] ....
Position:	Chef de division..
Years of experience:	24..

Would you like the name of your company be stated and acknowledged in this research?

Yes   *No X*

GUIDELINES FOR COMPLETING THE QUESTIONNAIRE;

This questionnaire estimates the relative importance of the expected consequences of failure and subway stations criticality to be further used for risk assessment. The comparison between factors will be conducted using a pairwise comparison matrix and a scale that expresses the qualitative judgments between criteria numerically. The scale indicates the relative importance through answering the question; *given a control criterion (Z) which of the two criteria (X) and (Y) is more dominant with respect to that criterion*. Kindly indicate your preference through circling the number representing your point of view. The following table illustrates an example.

Example:

In the table below, consider comparing ***"Social Impacts"*** (Criterion X) with ***"Financial Impacts"*** (Criterion Y) with respect to ***"Consequences of failure"***.

With respect to Z "Consequences of failure"

Indicate the relative importance of (X) on (Y) or vice versa

(X)	Absolute	Very Strong	Strong	Moderate	Equal	Moderate	Strong	Very Strong	Absolute	(Y)
Social Impacts	(9)	(7)	(5)	(3)	(1)	(3)	(5)	(7)	(9)	**Financial Impacts**
	(9)	(7)	(5)	(3)	(1)	(3)	(5)	(7)	(9)	**Operational Impacts**

*If you consider that "Social Impacts" is more important than "Financial Impacts" and the degree of importance is **"Strong"** then circle the number (5)*

If you consider that "Social Impacts" is equally important to "Financial Impacts" then circle the number (1)

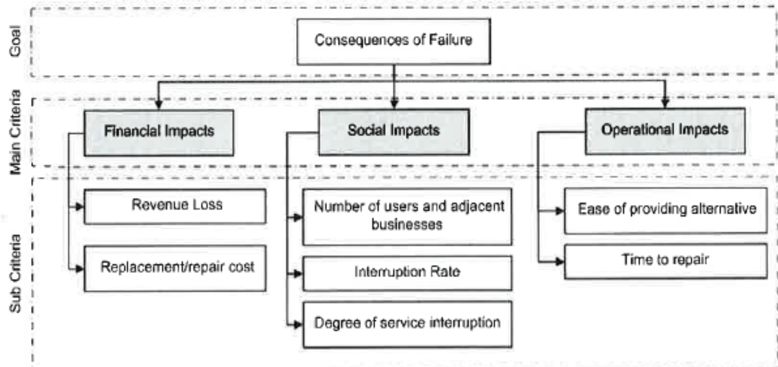
*If you consider that "Financial Impacts" is more important than "Social Impacts" and the degree of importance is **"Absolute"** then circle the number (9)*

*The same procedure is then followed when comparing **"Social Impacts"** with **"Operational Impacts"**.*

1

SECTION II: CONSEQUENCES OF FAILURE

The expected consequences of failure were identified and clustered as shown in the following figure. Please review the factors and fill in the following comparison matrices.



Comparison Matrices for Consequences of Failure:

Kindly indicate your preference of importance of different impacts of failure by circling the appropriate number that reflects your point of view;

A. Main criteria comparison with respect to goal " Consequences of failure" ;

With respect to Z "Consequences of failure"										
Indicate the relative importance of (X) on (Y) or vice versa										
(X)	Absolute	Very Strong	Strong	Moderate	Equal	Moderate	Strong	Very Strong	Absolute	(Y)
Social Impacts	(9)	(7)	(5)	(3)	(1)	(3)	(5)	(7)	(9)	Financial Impacts
	(9)	(7)	(5)	(3)	(1)	(3)	(5)	(7)	(9)	Operational Impacts

B. Main criteria comparison with respect to each other ;

With respect to Z "Financial Impacts"										
Indicate the relative importance of (X) on (Y) or vice versa										
(X)	Absolute	Very Strong	Strong	Moderate	Equal	Moderate	Strong	Very Strong	Absolute	(Y)
Social Impacts	(9)	(7)	(5)	(3)	(1)	(3)	(5)	(7)	(9)	Operational Impacts

With respect to Z "Social Impacts"										
(X)	Indicate the relative importance of (X) on (Y) or vice versa									(Y)
Financial Impacts	(9)	(7)	(5)	(3)	(1)	(3)	(5)	(7)	(9)	Operational Impacts

With respect to Z "Operational Impacts"										
(X)	Indicate the relative importance of (X) on (Y) or vice versa									(Y)
Financial Impacts	(9)	(7)	(5)	(3)	(1)	(3)	(5)	(7)	(9)	Social Impacts

C. Sub-criteria comparison with respect to main criteria;

With respect to Z "Financial Impacts of failure"										
(X)	**Indicate the relative importance of (X) on (Y) or vice versa**									**(Y)**
Loss of revenue	(9)	(7)	(5)	(3)	(1)	(3)	(5)	(7)	(9)	Replacement/repair cost

With respect to Z "Social Impacts of failure"										
(X)	**Indicate the relative importance of (X) on (Y) or vice versa**									**(Y)**
Degree of service interruption	(9)	(7)	(5)	(3)	(1)	(3)	(5)	(7)	(9)	Interruption rate
	(9)	(7)	(5)	(3)	(1)	(3)	(5)	(7)	(9)	Number of users and adjacent businesses

With respect to Z "Operational Impacts of failure"										
(X)	**Indicate the relative importance of (X) on (Y) or vice versa**									**(Y)**
Time to repair	(9)	(7)	(5)	(3)	(1)	(3)	(5)	(7)	(9)	Ease of providing alternative

- Are there any other impacts of failure that the questionnaire failed to address? If yes, please indicate them.

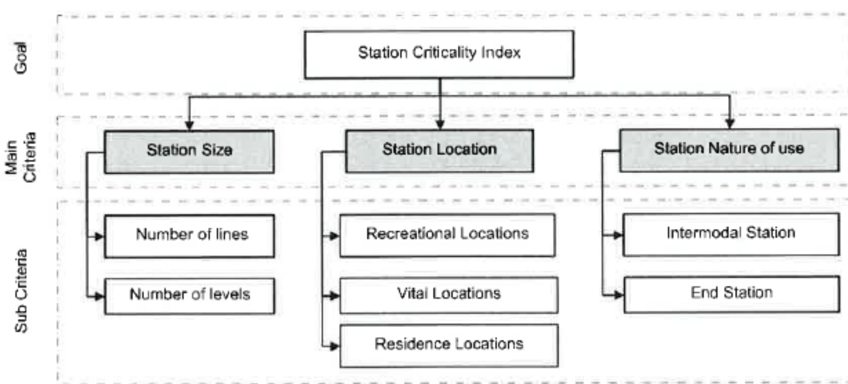
  ....

- Based on your experience, what is the maximum allowable number of service interruptions per year to sustain a good service reputation?

  less than 50 of more than 5 minutes.

SECTION III: STATION CRITICALITY

This section attempts to measure the relative criticality of subway stations. Based on the literature review and case studies, the factors contributing to station criticality were identified as illustrated in the following figure.



Comparison Matrices for Criticality Index;

Kindly indicate your preference of importance of different criticality factors by circling the appropriate number that reflects your point of view;

A. Main criteria comparison with respect to goal " Station Criticality" ;

With respect to Z "Station Criticality"										
Indicate the relative importance of (X) on (Y) or vice versa										
(X)	Absolute	Very Strong	Strong	Moderate	Equal	Moderate	Strong	Very Strong	Absolute	(Y)
Station Size	(9)	(7)	(5)	(3)	(1)	(3)	(5)	(7)	(9)	Station Location
	(9)	(7)	(5)	(3)	(1)	(3)	(5)	(7)	(9)	Station Nature of use

B. Main criteria comparison with respect to each other ;

With respect to Z "Station Size"										
(X)	Indicate the relative importance of (X) on (Y) or vice versa									(Y)
Station Location	(9)	(7)	(5)	(3)	(1)	(3)	(5)	(7)	(9)	Station Nature of use

With respect to Z "Station Location"										
(X)	Indicate the relative importance of (X) on (Y) or vice versa									(Y)
Station Size	(9)	(7)	(5)	(3)	(1)	(3)	(5)	(7)	(9)	Station Nature of use

With respect to Z "Station Nature of use"										
(X)	Indicate the relative importance of (X) on (Y) or vice versa									(Y)
Station Size	(9)	(7)	(5)	(3)	(1)	(3)	(5)	(7)	(9)	Station Location

C. Sub-criteria comparison with respect to main criteria;

With respect to Z "Station Size"										
(X)	Indicate the relative importance of (X) on (Y) or vice versa									(Y)
Number of levels	(9)	(7)	(5)	(3)	(1)	(3)	(5)	(7)	(9)	Number of lines

With respect to Z "Station Location"										
(X)	Indicate the relative importance of (X) on (Y) or vice versa									(Y)
High residence area	(9)	(7)	(5)	(3)	(1)	(3)	(5)	(7)	(9)	Medium residence area
	(9)	(7)	(5)	(3)	(1)	(3)	(5)	(7)	(9)	Low residence area
	(9)	(7)	(5)	(3)	(1)	(3)	(5)	(7)	(9)	Recreational area
	(9)	(7)	(5)	(3)	(1)	(3)	(5)	(7)	(9)	University/School/Hospital

With respect to Z "Station Nature of use"										
(X)	Indicate the relative importance of (X) on (Y) or vice versa									(Y)
End Station	(9)	(7)	(5)	(3)	(1)	(3)	(5)	(7)	(9)	Intermodal Station

- Are there any other factors of station criticality that the questionnaire failed to address? If yes, please indicate them.

....

SECTION I: GENERAL INFORMATION

Thank you for taking part in this questionnaire; your effort and time are highly appreciated.

This questionnaire is conducted as a part of an ongoing research for a PhD thesis at Concordia University under the title of: An Integrated Risk-based Asset Management Tools for Subway Systems. The purpose of this research is to analyze the impacts of failure expected from subway elements failure (Section II) and subway stations importance with respect to each other (Section III).
The information Collected from the questionnaire will be used for academic research only and is highly confidential. All the respondent information will be kept anonymous.

Please indicate the name[redacted]***ll answers reflect my personal opinion and not those of the company***
Name: ....
Position: ......Senior Engineer...
Years of experience: ....18...
Would you like the name of your company be stated and acknowledged in this research?
Yes ***No***

GUIDELINES FOR COMPLETING THE QUESTIONNAIRE;

This questionnaire estimates the relative importance of the expected consequences of failure and subway stations criticality to be further used for risk assessment. The comparison between factors will be conducted using a pairwise comparison matrix and a scale that expresses the qualitative judgments between criteria numerically. The scale indicates the relative importance through answering the question; *given a control criterion (Z) which of the two criteria (X) and (Y) is more dominant with respect to that criterion*. Kindly indicate your preference through circling the number representing your point of view. The following table illustrates an example.

Example:

In the table below, consider comparing ***"Social Impacts"*** (Criterion X) with ***"Financial Impacts"*** (Criterion Y) with respect to ***"Consequences of failure"***.

With respect to Z "Consequences of failure"										
Indicate the relative importance of (X) on (Y) or vice versa										
(X)	Absolute	Very Strong	Strong	Moderate	Equal	Moderate	Strong	Very Strong	Absolute	**(Y)**
Social Impacts	(9)	(7)	(5)	(3)	(1)	(3)	(5)	(7)	(9)	Financial Impacts
	(9)	(7)	(5)	(3)	(1)	(3)	(5)	(7)	(9)	Operational Impacts

*If you consider that "Social Impacts" is more important than "Financial Impacts" and the degree of importance is **"Strong"** then circle the number (5)*

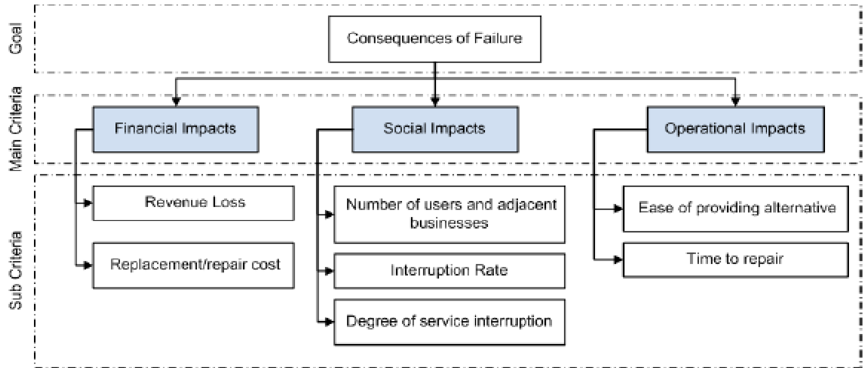
If you consider that "Social Impacts" is equally important to "Financial Impacts" then circle the number (1)

*If you consider that "Financial Impacts" is more important than "Social Impacts" and the degree of importance is **"Absolute"** then circle the number (9)*

*The same procedure is then followed when comparing **"Social Impacts"** with **"Operational Impacts"**.*

SECTION II: CONSEQUENCES OF FAILURE

The expected consequences of failure were identified and clustered as shown in the following figure. Please review the factors and fill in the following comparison matrices.



Comparison Matrices for Consequences of Failure:

Kindly indicate your preference of importance of different impacts of failure by circling the appropriate number that reflects your point of view;

A. Main criteria comparison with respect to goal " Consequences of failure" ;

With respect to Z "Consequences of failure"										
Indicate the relative importance of (X) on (Y) or vice versa										
(X)	Absolute	Very Strong	**Strong**	Moderate	Equal	Moderate	Strong	Very Strong	Absolute	(Y)
Social Impacts	(9)	(7)	**(5)**	(3)	(1)	(3)	(5)	(7)	(9)	Financial Impacts
	(9)	(7)	**(5)**	(3)	(1)	(3)	(5)	(7)	(9)	Operational Impacts

B. Main criteria comparison with respect to each other ;

With respect to Z "Financial Impacts"										
Indicate the relative importance of (X) on (Y) or vice versa										
(X)	Absolute	Very Strong	**Strong**	Moderate	Equal	Moderate	Strong	Very Strong	Absolute	(Y)
Social Impacts	(9)	(7)	**(5)**	(3)	(1)	(3)	(5)	(7)	(9)	Operational Impacts

With respect to Z "Social Impacts"										
(X)	Indicate the relative importance of (X) on (Y) or vice versa									(Y)
Financial Impacts	(9)	(7)	(5)	(3)	(1)	(3)	**(5)**	(7)	(9)	Operational Impacts

With respect to Z "Operational Impacts"										
(X)	Indicate the relative importance of (X) on (Y) or vice versa									(Y)
Financial Impacts	(9)	(7)	(5)	(3)	(1)	(3)	**(5)**	(7)	(9)	Social Impacts

C. Sub-criteria comparison with respect to main criteria;

With respect to Z "Financial Impacts of failure"										
(X)	**Indicate the relative importance of (X) on (Y) or vice versa**									**(Y)**
Loss of revenue	(9)	(7)	**(5)**	(3)	(1)	(3)	(5)	(7)	(9)	Replacement/repair cost

With respect to Z "Social Impacts of failure"										
(X)	**Indicate the relative importance of (X) on (Y) or vice versa**									**(Y)**
Degree of service interruption	(9)	(7)	(5)	(3)	(1)	(3)	**(5)**	(7)	(9)	Interruption rate
	(9)	(7)	(5)	(3)	(1)	(3)	**(5)**	(7)	(9)	Number of users and adjacent businesses

With respect to Z "Operational Impacts of failure"										
(X)	**Indicate the relative importance of (X) on (Y) or vice versa**									**(Y)**
Time to repair	(9)	(7)	(5)	(3)	(1)	(3)	**(5)**	(7)	(9)	Ease of providing alternative

- Are there any other impacts of failure that the questionnaire failed to address? If yes, please indicate them.

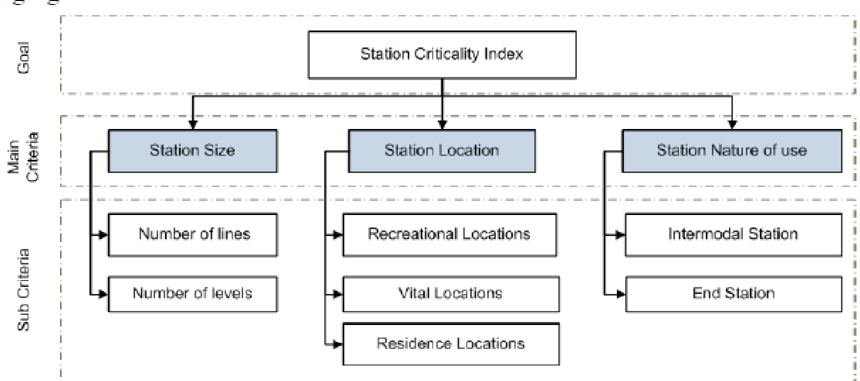
....

- Based on your experience, what is the maximum allowable number of service interruptions per year to sustain a good service reputation?

.........................25..

SECTION III: STATION CRITICALITY

This section attempts to measure the relative criticality of subway stations. Based on the literature review and case studies, the factors contributing to station criticality were identified as illustrated in the following figure.



Comparison Matrices for Criticality Index;

Kindly indicate your preference of importance of different criticality factors by circling the appropriate number that reflects your point of view;

A. Main criteria comparison with respect to goal " Station Criticality" ;

With respect to Z "Station Criticality"										
Indicate the relative importance of (X) on (Y) or vice versa										
(X)	Absolute	Very Strong	Strong	Moderate	Equal	Moderate	Strong	Very Strong	Absolute	(Y)
Station Size	(9)	(7)	(5)	(3)	(1)	(3)	(5)	**(7)**	(9)	Station Location
	(9)	(7)	(5)	(3)	(1)	(3)	(5)	**(7)**	(9)	Station Nature of use

B. Main criteria comparison with respect to each other ;

With respect to Z "Station Size"										
(X)	Indicate the relative importance of (X) on (Y) or vice versa									(Y)
Station Location	(9)	**(7)**	(5)	(3)	(1)	(3)	(5)	(7)	(9)	Station Nature of use

With respect to Z "Station Location"										
(X)	Indicate the relative importance of (X) on (Y) or vice versa									(Y)
Station Size	(9)	(7)	(5)	(3)	**(1)**	(3)	(5)	(7)	(9)	Station Nature of use

With respect to Z "Station Nature of use"										
(X)	Indicate the relative importance of (X) on (Y) or vice versa									(Y)
Station Size	(9)	(7)	(5)	(3)	(1)	(3)	(5)	**(7)**	(9)	Station Location

C. Sub-criteria comparison with respect to main criteria;

With respect to Z "Station Size"										
(X)	Indicate the relative importance of (X) on (Y) or vice versa									(Y)
Number of levels	(9)	(7)	(5)	(3)	**(1)**	(3)	(5)	(7)	(9)	Number of lines

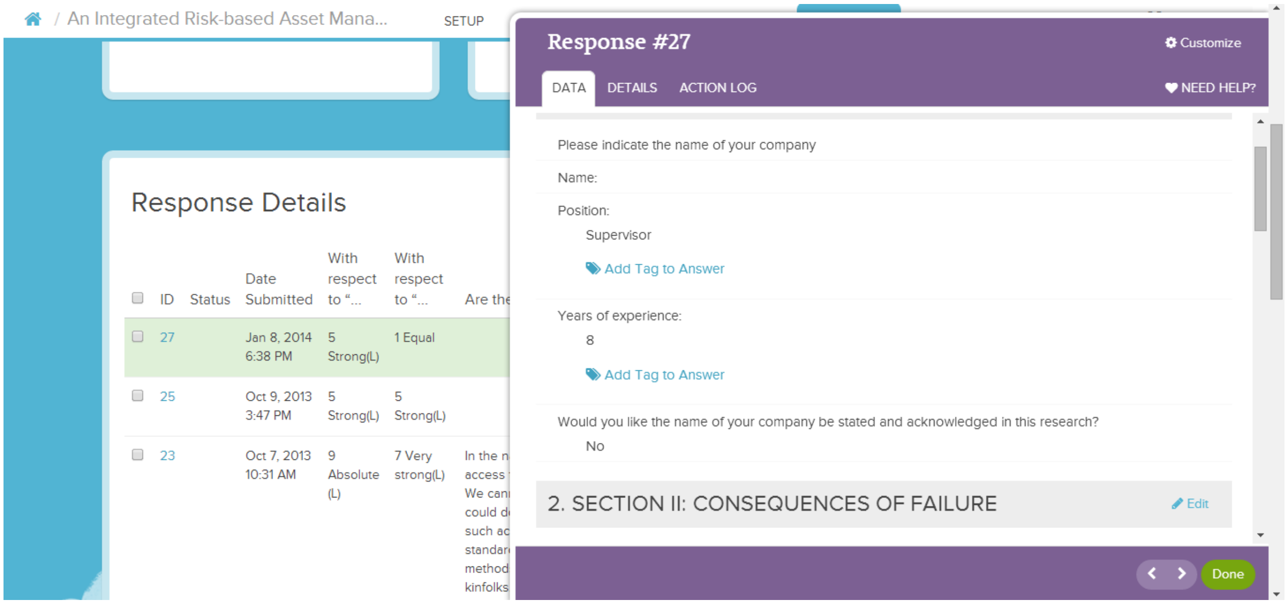
With respect to Z "Station Location"										
(X)	Indicate the relative importance of (X) on (Y) or vice versa									(Y)
High residence area	(9)	(7)	**(5)**	(3)	(1)	(3)	(5)	(7)	(9)	Medium residence area
	(9)	(7)	**(5)**	(3)	(1)	(3)	(5)	(7)	(9)	Low residence area
	(9)	(7)	(5)	(3)	**(1)**	(3)	(5)	(7)	(9)	Recreational area
	(9)	(7)	(5)	(3)	**(1)**	(3)	(5)	(7)	(9)	University/School/Hospital

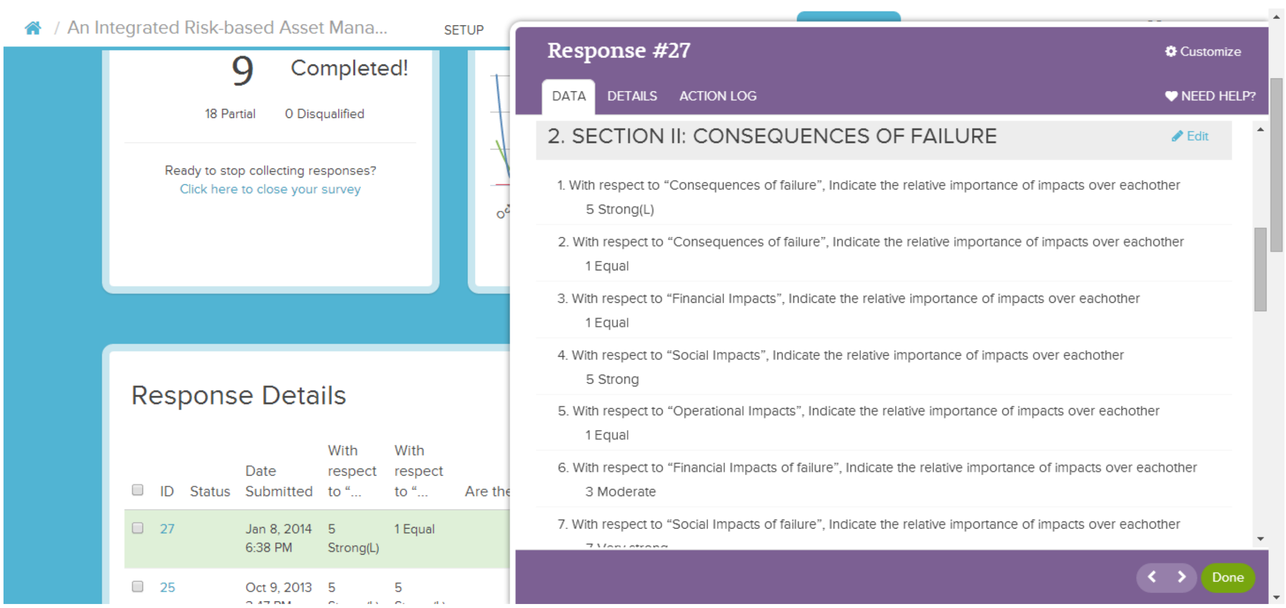
With respect to Z "Station Nature of use"										
(X)	Indicate the relative importance of (X) on (Y) or vice versa									(Y)
End Station	(9)	**(7)**	(5)	(3)	(1)	(3)	(5)	(7)	(9)	Intermodal Station

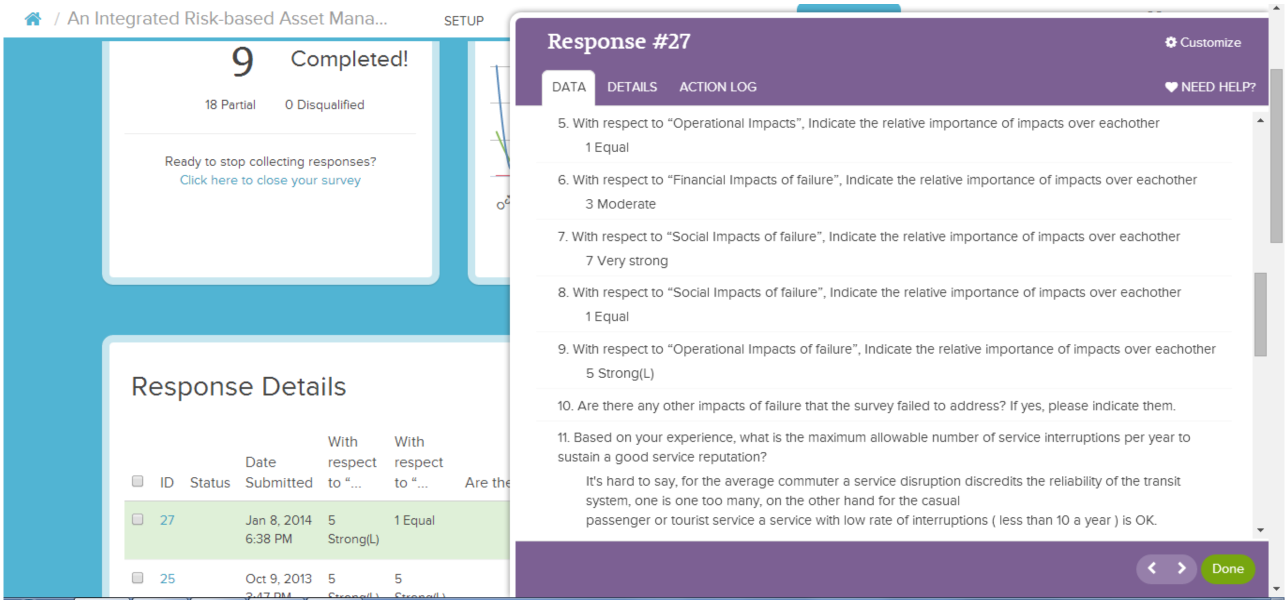
- Are there any other factors of station criticality that the questionnaire failed to address? If yes, please indicate them.

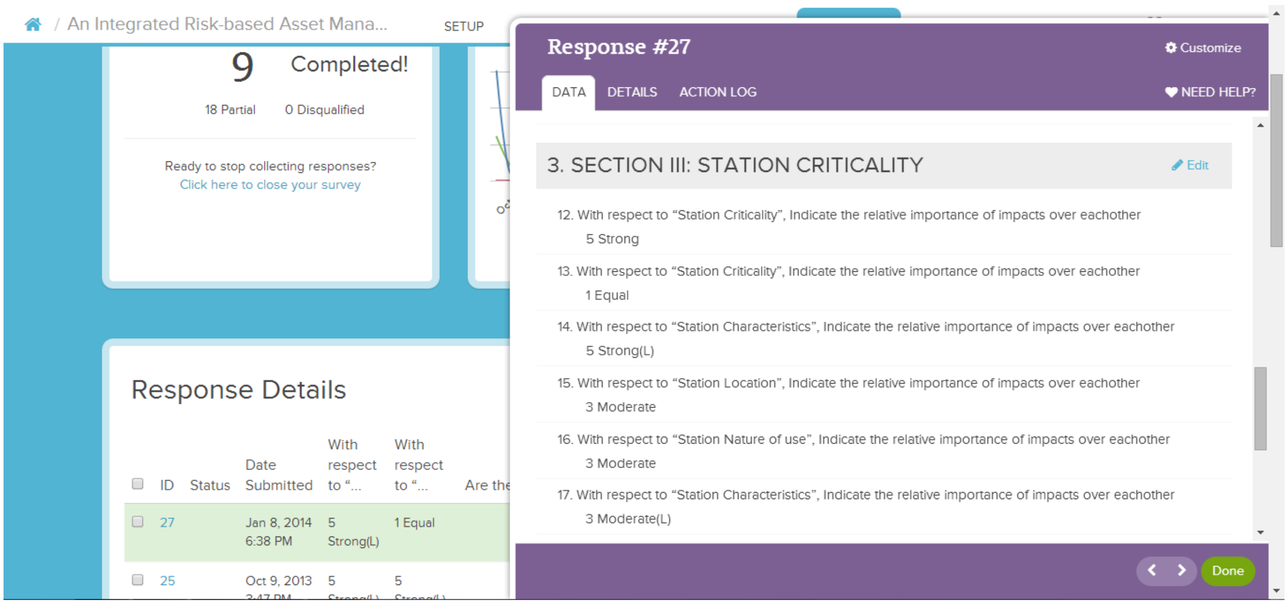
....

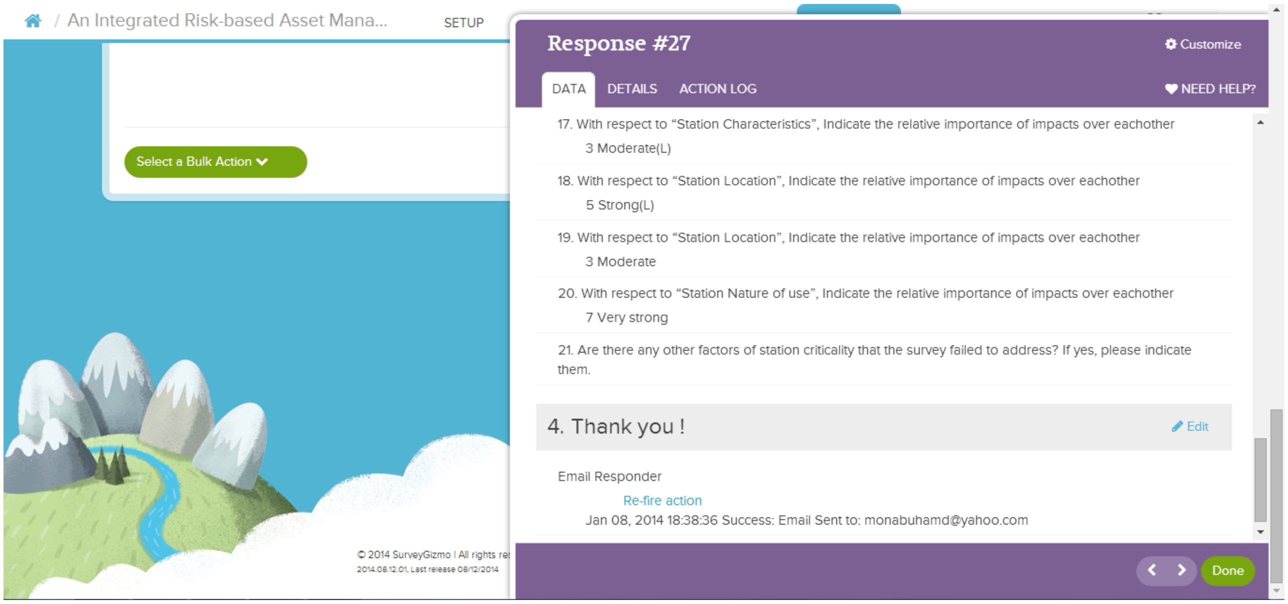
SAMPLE ONLINE-FILLED QUESTIONNAIRE

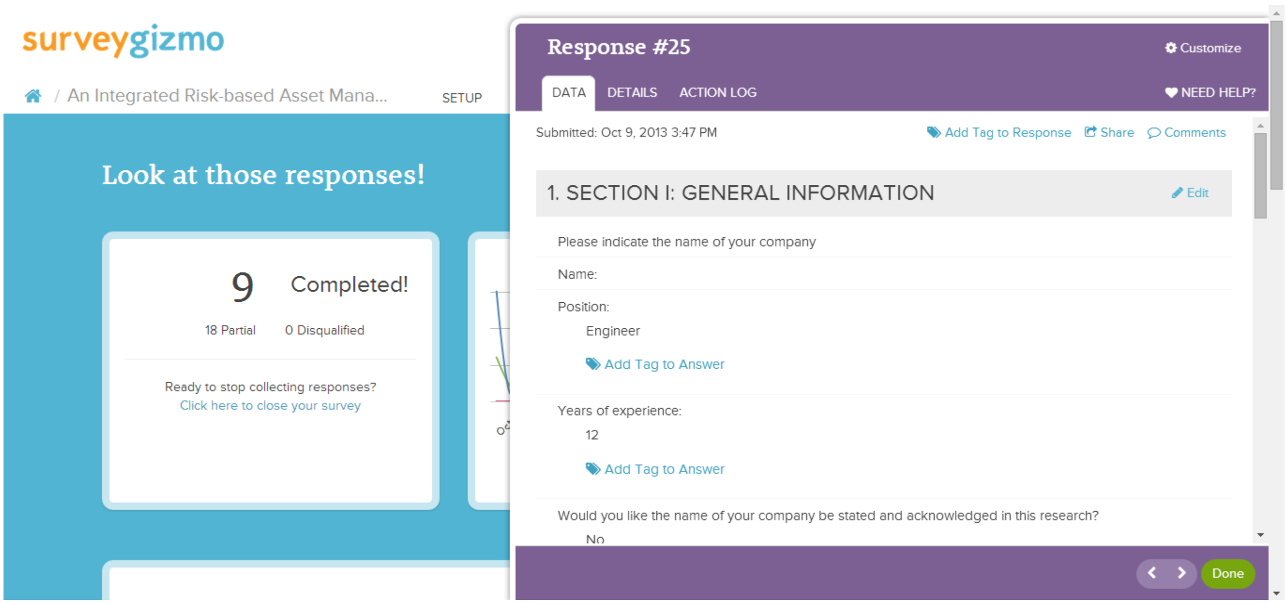


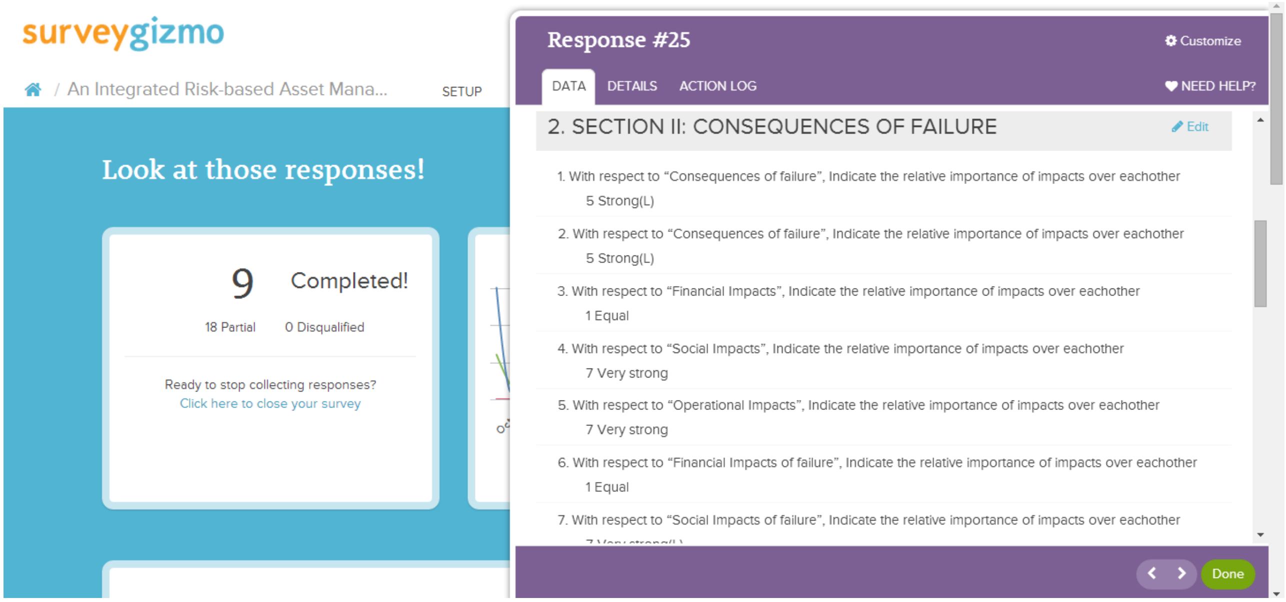


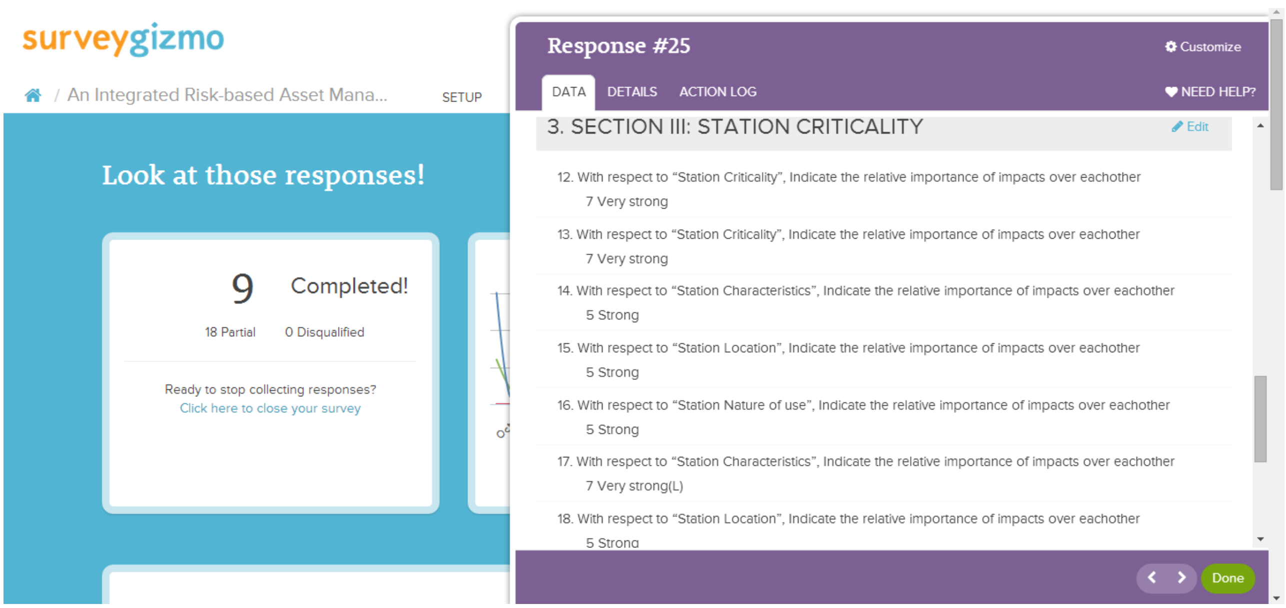

An Integrated Risk-based Asset Mana...
SETUP
9 Completed!
18 Partial
0 Disqualified
Ready to stop collecting responses?
Click here to close your survey
Response Details
ID Status Date Submitted With respect to "... With respect to "... Are the
27 Jan 8, 2014 6:38 PM 5 Strong(L) 1 Equal
25 Oct 9, 2013 5 5
Response #27
Customize
DATA DETAILS ACTION LOG
NEED HELP?
5. With respect to "Operational Impacts", Indicate the relative importance of impacts over eachother
1 Equal
6. With respect to "Financial Impacts of failure", Indicate the relative importance of impacts over eachother
3 Moderate
7. With respect to "Social Impacts of failure", Indicate the relative importance of impacts over eachother
7 Very strong
8. With respect to "Social Impacts of failure", Indicate the relative importance of impacts over eachother
1 Equal
9. With respect to "Operational Impacts of failure", Indicate the relative importance of impacts over eachother
5 Strong(L)
10. Are there any other impacts of failure that the survey failed to address? If yes, please indicate them.
11. Based on your experience, what is the maximum allowable number of service interruptions per year to sustain a good service reputation?
It's hard to say, for the average commuter a service disruption discredits the reliability of the transit system, one is one too many, on the other hand for the casual passenger or tourist service a service with low rate of interruptions (less than 10 a year) is OK.
Done

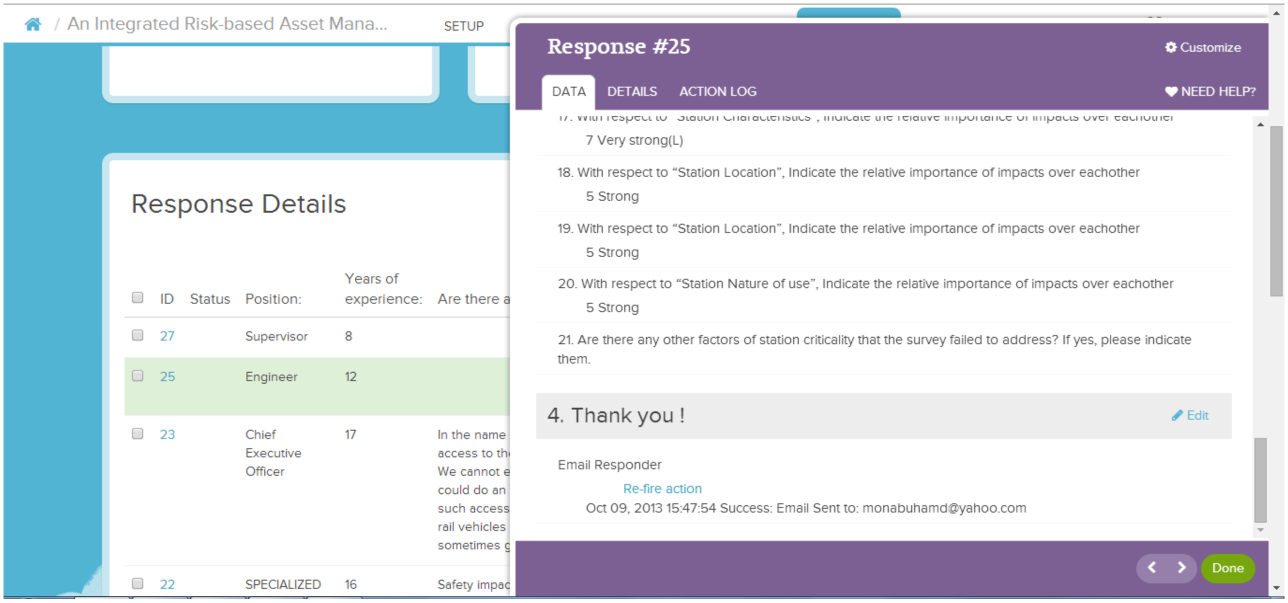

An Integrated Risk-based Asset Mana...
SETUP
9 Completed!
18 Partial
0 Disqualified
Ready to stop collecting responses?
Click here to close your survey
Response Details
ID Status Date Submitted With respect to "... With respect to "... Are the
27 Jan 8, 2014 6:38 PM 5 Strong(L) 1 Equal
25 Oct 9, 2013 5 5
Response #27
Customize
DATA DETAILS ACTION LOG
NEED HELP?
3. SECTION III: STATION CRITICALITY
Edit
12. With respect to "Station Criticality", Indicate the relative importance of impacts over eachother
5 Strong
13. With respect to "Station Criticality", Indicate the relative importance of impacts over eachother
1 Equal
14. With respect to "Station Characteristics", Indicate the relative importance of impacts over eachother
5 Strong(L)
15. With respect to "Station Location", Indicate the relative importance of impacts over eachother
3 Moderate
16. With respect to "Station Nature of use", Indicate the relative importance of impacts over eachother
3 Moderate
17. With respect to "Station Characteristics", Indicate the relative importance of impacts over eachother
3 Moderate(L)
Done


An Integrated Risk-based Asset Mana...
SETUP
Select a Bulk Action
© 2014 SurveyGizmo | All rights re
Response #27
Customize
DATA
DETAILS
ACTION LOG
NEED HELP?
17. With respect to "Station Characteristics", Indicate the relative importance of impacts over eachother
3 Moderate(L)
18. With respect to "Station Location", Indicate the relative importance of impacts over eachother
5 Strong(L)
19. With respect to "Station Location", Indicate the relative importance of impacts over eachother
3 Moderate
20. With respect to "Station Nature of use", Indicate the relative importance of impacts over eachother
7 Very strong
21. Are there any other factors of station criticality that the survey failed to address? If yes, please indicate them.
4. Thank you !
Edit
Email Responder
Re-fire action
Jan 08, 2014 18:38:36 Success: Email Sent to: monabuhamd@yahoo.com
Done


surveygizmo
An Integrated Risk-based Asset Mana...
SETUP
Look at those responses!
9
Completed!
18 Partial
0 Disqualified
Ready to stop collecting responses?
Click here to close your survey
Response #25
Customize
DATA
DETAILS
ACTION LOG
NEED HELP?
Submitted: Oct 9, 2013 3:47 PM
Add Tag to Response
Share
Comments
1. SECTION I: GENERAL INFORMATION
Edit
Please indicate the name of your company
Name:
Position:
Engineer
Add Tag to Answer
Years of experience:
12
Add Tag to Answer
Would you like the name of your company be stated and acknowledged in this research?
No
Done


surveygizmo
An Integrated Risk-based Asset Mana...
SETUP
Look at those responses!
9 Completed!
18 Partial
0 Disqualified
Ready to stop collecting responses?
Click here to close your survey
Response #25
Customize
DATA
DETAILS
ACTION LOG
NEED HELP?
2. SECTION II: CONSEQUENCES OF FAILURE
Edit
1. With respect to "Consequences of failure", Indicate the relative importance of impacts over eachother
5 Strong(L)
2. With respect to "Consequences of failure", Indicate the relative importance of impacts over eachother
5 Strong(L)
3. With respect to "Financial Impacts", Indicate the relative importance of impacts over eachother
1 Equal
4. With respect to "Social Impacts", Indicate the relative importance of impacts over eachother
7 Very strong
5. With respect to "Operational Impacts", Indicate the relative importance of impacts over eachother
7 Very strong
6. With respect to "Financial Impacts of failure", Indicate the relative importance of impacts over eachother
1 Equal
7. With respect to "Social Impacts of failure", Indicate the relative importance of impacts over eachother
Done


surveygizmo
An Integrated Risk-based Asset Mana...
SETUP
Look at those responses!
9 Completed!
18 Partial
0 Disqualified
Ready to stop collecting responses?
Click here to close your survey
Response #25
Customize
DATA
DETAILS
ACTION LOG
NEED HELP?
3. SECTION III: STATION CRITICALITY
Edit
12. With respect to "Station Criticality", Indicate the relative importance of impacts over eachother
7 Very strong
13. With respect to "Station Criticality", Indicate the relative importance of impacts over eachother
7 Very strong
14. With respect to "Station Characteristics", Indicate the relative importance of impacts over eachother
5 Strong
15. With respect to "Station Location", Indicate the relative importance of impacts over eachother
5 Strong
16. With respect to "Station Nature of use", Indicate the relative importance of impacts over eachother
5 Strong
17. With respect to "Station Characteristics", Indicate the relative importance of impacts over eachother
7 Very strong(L)
18. With respect to "Station Location", Indicate the relative importance of impacts over eachother
Done



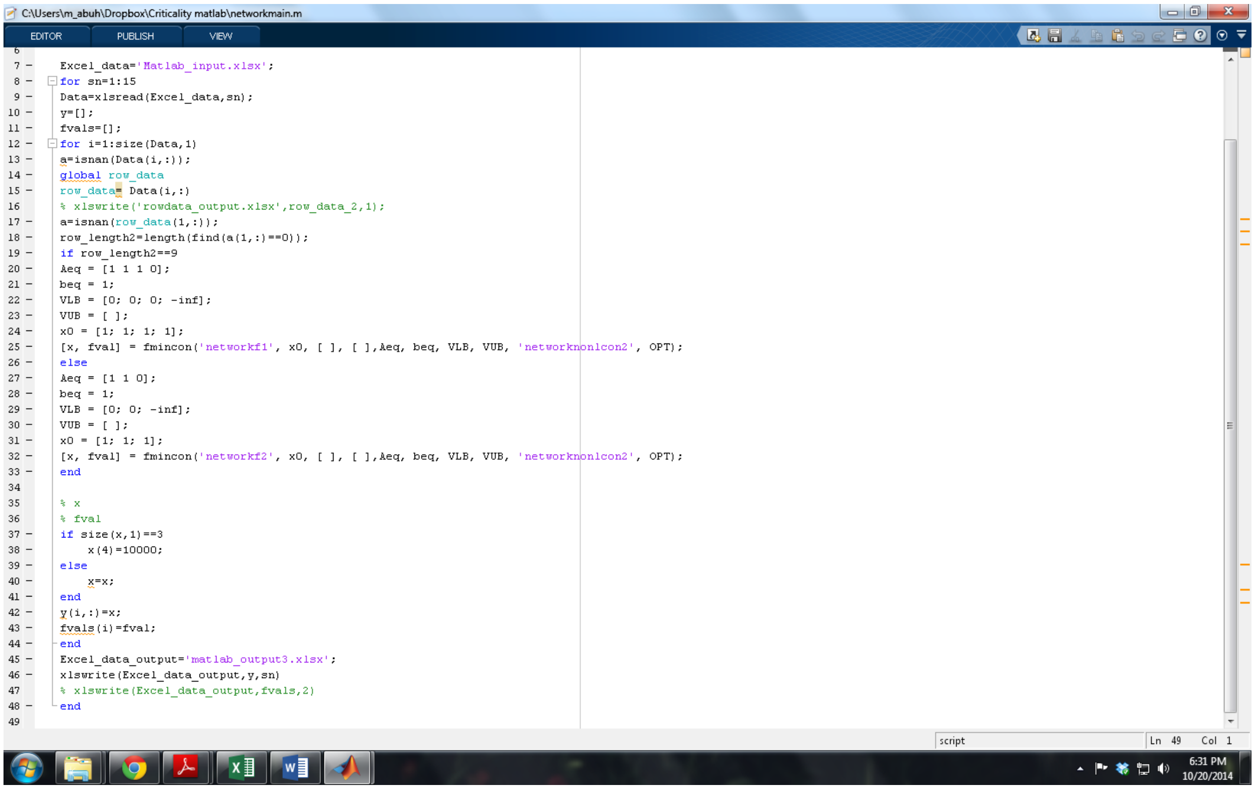
An Integrated Risk-based Asset Mana...
SETUP
Response Details
ID
Status
Position:
Years of experience:
27
Supervisor
8
25
Engineer
12
23
Chief Executive Officer
17
22
SPECIALIZED
16
Response #25
Customize
DATA
DETAILS
ACTION LOG
NEED HELP?
7 Very strong(L)
18. With respect to "Station Location", Indicate the relative importance of impacts over eachother
5 Strong
19. With respect to "Station Location", Indicate the relative importance of impacts over eachother
5 Strong
20. With respect to "Station Nature of use", Indicate the relative importance of impacts over eachother
5 Strong
21. Are there any other factors of station criticality that the survey failed to address? If yes, please indicate them.
4. Thank you !
Edit
Email Responder
Re-fire action
Oct 09, 2013 15:47:54 Success: Email Sent to: monabuhamd@yahoo.com
Done

APPENDIX B

FUZZY ANP CODE

```
Excel_data='Matlab_input.xlsx';
for sn=1:15
Data=xlsread(Excel_data,sn);
y=[];
fvals=[];
for i=1:size(Data,1)
a=isnan(Data(i,:));
global row_data
row_data= Data(i,:)
% xlswrite('rowdata_output.xlsx',row_data_2,1);
a=isnan(row_data(1,:));
row_length2=length(find(a(1,:)==0));
if row_length2==9
Aeq = [1 1 1 0];
beq = 1;
VLB = [0; 0; 0; -inf];
VUB = [ ];
x0 = [1; 1; 1; 1];
[x, fval] = fmincon('networkf1', x0, [ ], [ ],Aeq, beq, VLB, VUB,
'networknonlcon2', OPT);
else
Aeq = [1 1 0];
beq = 1;
VLB = [0; 0; -inf];
VUB = [ ];
x0 = [1; 1; 1];
[x, fval] = fmincon('networkf2', x0, [ ], [ ],Aeq, beq, VLB, VUB,
'networknonlcon2', OPT);
end

% x
% fval
if size(x,1)==3
    x(4)=10000;
else
    x=x;
end
y(i,:)=x;
fvals(i)=fval;
end
Excel_data_output='matlab_output3.xlsx';
xlswrite(Excel_data_output,y,sn)
% xlswrite(Excel_data_output,fvals,2)
end
```



C:\Users\m_abuh\Dropbox\Criticality matlab\networkmain.m

EDITOR PUBLISH VIEW

```matlab
Excel_data='Matlab_input.xlsx';
for sn=1:15
Data=xlsread(Excel_data,sn);
y=[];
fvals=[];
for i=1:size(Data,1)
a=isnan(Data(i,:));
global row_data
row_data= Data(i,:)
% xlswrite('rowdata_output.xlsx',row_data_2,1);
a=isnan(row_data(1,:));
row_length2=length(find(a(1,:)==0));
if row_length2==9
Aeq = [1 1 1 0];
beq = 1;
VLB = [0; 0; 0; -inf];
VUB = [ ];
x0 = [1; 1; 1; 1];
[x, fval] = fmincon('networkf1', x0, [ ], [ ],Aeq, beq, VLB, VUB, 'networknonlcon2', OPT);
else
Aeq = [1 1 0];
beq = 1;
VLB = [0; 0; -inf];
VUB = [ ];
x0 = [1; 1; 1];
[x, fval] = fmincon('networkf2', x0, [ ], [ ],Aeq, beq, VLB, VUB, 'networknonlcon2', OPT);
end

% x
% fval
if size(x,1)==3
    x(4)=10000;
else
    x=x;
end
y(i,:)=x;
fvals(i)=fval;
end
Excel_data_output='matlab_output3.xlsx';
xlswrite(Excel_data_output,y,sn)
% xlswrite(Excel_data_output,fvals,2)
end
```

script Ln 49 Col 1

6:31 PM 10/20/2014