INFRASTRUCTURE PERFORMANCE ASSESSMENT OF SUBWAY NETWORKS

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This is to certify that the thesis prepared

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complies with the regulations of the University and meets the accepted standards with respect to originality and quality.

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ABSTRACT

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Subway networks are the most crucial transit systems of large cities. According to reports, ridership is growing and will continue to do so in the following decade. The 2013 America's Infrastructure Report Card evaluated transit infrastructure with a grade of D which is translated in poor condition. Large amount of capital investment is required, for instance, the "Société de Transport de Montréal" has assigned around $500 Million for renovation works of its infrastructure. Despite that, transit authorities so far have been relying on empirical management approaches based on engineering judgment and decision makers' preference. Few models are currently found in which, they either focus on stations solely or examine structural performance only. Taking into account the deterioration severity and the amount of passengers, the duty of proper subway asset management becomes a critical public safety issue. New models are required since they will ensure passenger safety, assist in repair planning and optimize budget allocation.

This research is aiming at developing a model for subway network performance assessment including structural, electrical and mechanical infrastructure. To achieve this objective, a typical breakdown is introduced including network, lines, stations, tunnels and components. The methodology passes through two main phases. First, a condition assessment model for components is developed based on identified defects. Subsequently, the condition index of stations and tunnels is calculated, followed by the rating of subway lines and the entire network. The Analytic Hierarchy and Network Processes, along with the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) and systems reliability are utilized in the computation procedure. Second, a condition prediction model is developed using Weibull theory, which constructs deterioration curves for all the network levels. In addition, the above two phases are incorporated in a user-friendly computerized application.

Data for the relative importance weights are collected through on-line surveys sent to subway experts. It is concluded that components related to passenger safety and client services, such as emergency lightning and escalators, are the most important of the subway network. The developed methodology is also applied to a sub-network of Athens Metro system. The results show that stations are recording condition indexes of more than 7/10 and the network has satisfactory performance. Repair actions need to be planned for 2020. This research provides a new subway network asset management tool that considers all aspects of infrastructure, measures the condition based on actual defects and offers future condition prediction. The outcomes of this research are relevant to transit authorities, asset managers, engineers and researchers.

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LIST OF ABBREVIATIONS

AHP	Analytic Hierarchy Process
ANP	Analytic Network Process
APTA	American Public Transportation Authority
ASCE	American Society of Civil Engineers
CI	Condition Index
CTA	Chicago Transit Authority
MCDM	Multi-Criteria Decision Making
MTA NYCT	Metropolitan Transit Authority New York City Transit
STM	Société de Transport de Montréal
STREM	Structural, Electrical and Mechanical
TOPSIS	Technique for Order Preference by Similarity to Ideal Solution
TTC	Toronto Transit Commission

1 Introduction

1.1 Introduction

Civil infrastructure has always been a vital ingredient of community living and a major contributor to the economic status of countries and cities. It is nowadays inconceivable for an advanced and developing city not to offer underground transportation services. In North America, Metro systems have been in operation since the early or mid-20th century. The amount of passengers choosing the underground rail for their daily commute continues to grow. According to the American Public Transportation Association (APTA) quarter report (APTA, 2013), in Montreal, 175 million trips took place in 2012, whereas in the case of New York City, that number reaches around 2.5 billion. Toronto recorded around 320 million trips, Washington D.C. 280 million and Chicago 230 million trips. Ridership illustrates an ascending trend in the next decade (APTA, 2013).

Currently, the issue of infrastructure deterioration is rising in North America including bridges, highways, water networks and public buildings (ASCE, 2013). Transit systems inevitably cannot be excluded from that list. The causes are clear, first of all a) the aging of infrastructure since some systems have been around for over 100 years, then b) the increasing traffic load and demand for transportation and the inability of current systems to absorb this growing demand and finally c) improper maintenance and repair planning by transit authorities. According to America's Infrastructure Report Card for 2013, transit infrastructure was assigned the grade of D and was characterized as poor (ASCE, 2013). In a report prepared for the Chicago Transit Authority (CTA), almost 40% of its rail stations have surpassed their anticipated service life and face extensive deterioration (Gallucci et al. 2012).

Reliability, attractiveness, level of service and safety are among the objectives of every transit system worldwide (Kepaptsoglou et al. 2012). Transit Authorities are spending a significant amount of budget for the restoration of the current state of their infrastructure in an attempt to fulfill their goals. The net replacement value of the Montreal Metro System is considered to be 14.5 $ billion (Chaussée, 2012). The "Société de Transport de Montréal" (STM) had assigned $ 60 million for the "Reno-Stations" program (stations renovations) between 1998 and 2000 (STM, 2011), $ 75 million more for the "Reno-Stations II" program (2006 – 2011), $ 140 million for the "Berri Project" (renovation of the network's most important station" and around $ 250 million for the "Reno-Infra" program (renovation of electrical and mechanical infrastructure) in the period 2011 – 2016 (STM, 2011). Toronto transit Commission (TTC) has approved a total expenditure of $ 4.5 billion in the next decade's plan (2013-2022) for metro transit improvement and expansion (TTC, 2012).

The deterioration severity and the amount of passengers using the subway systems, make the task of metro infrastructure condition assessment a crucial public safety issue. The evaluation of subway performance should consider all types of infrastructures, such as electrical and mechanical and not be limited to the structural aspects of the system. Accordingly, the condition rating should extend to all levels of a subway system, from station components to subway lines and the entire network. Transit authorities need to develop proper asset management tools in order to enhance passenger safety, increase current system performance, assist in the optimum maintenance, repair and rehabilitation planning and eliminate budget mismanagement.

1.2 Research Motivation and Problem Statement

This research has been inspired by the looming need of transit authorities to develop asset management tools to target the current issues of deterioration in subway networks. In accordance with the importance of subways as transit systems, such tools become an urgent need. Certain limitations have been identified and require improvement. Currently, most metro operators and transit authorities use empirical approaches based on engineering judgment and decision makers' preference or refer to external consultants when it comes to condition assessment. In addition, some of the few identified existing metro performance evaluation techniques include criteria of various natures and customer satisfaction surveys without focusing on the infrastructure. Other developed condition assessment models are mostly applicable to stations and do not examine subways from the perspective of a network. Another major deficiency lies to the fact that electrical and mechanical infrastructures of subways are often excluded from the condition rating approaches which tend to give more emphasis to the structural aspects of the system. Moreover, condition prediction models need to be developed for the case of subways as well since they are an essential module of asset management tools allowing the future performance forecast of the system. From another, more technical point of view, the mathematical techniques implemented so far for subway evaluation have been either very simplistic (e.g. point allocation system) or very complex and demanding in data input, when they need to be sound in their logic and fast in their implementation. Finally, there are very few automated tools in a software form for the purpose of subway condition assessment in comparison with other types of infrastructures such as bridges, pavements and buildings.

1.3 Research Objectives

With reference to the above stated problem and the limitations identified from the currently implemented approaches, this study aims to respond to the need for a new condition assessment methodology for subway systems. This new model should include electrical, mechanical and structural features and examine the condition from a network point of view. Consequently, the objectives of this research can be defined as follows:

1) Identify and study the different components of subway systems and their deterioration characteristics.
2) Develop integrated structural, electrical and mechanical condition assessment and prediction models for subway networks.
3) Automate the developed models using a user-friendly computer application.

1.4 Research Methodology

The product of this research is a subway network condition assessment and prediction model that attempts to cover the limitations of current approaches and fulfill the stated research objectives. An extensive literature review is performed initially to identify existing approaches utilized by transit authorities and researchers, as well as examine mathematical tools frequently implemented to solve such problems. A generic diagram of the research methodology is shown in Figure 1.1. It should be noted that the methodology part is actually consisting of 2 phases, the condition assessment model and the condition prediction model.

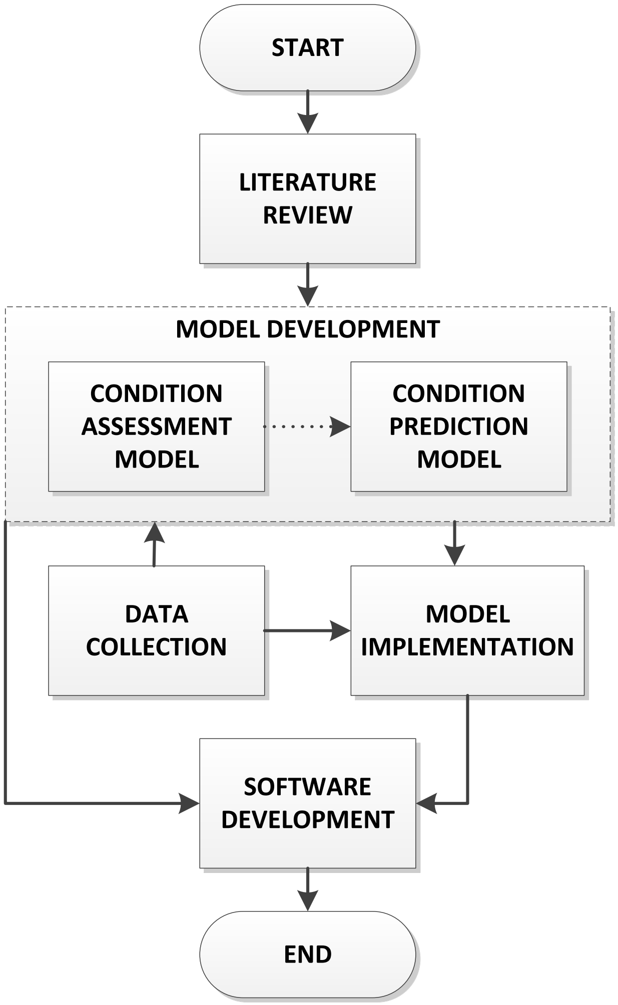


Figure 1.1 Research Flowchart

The developed performance assessment model can be described in the following discrete steps:

- Identify a subway network hierarchy of components.
- Identify a hierarchy of the most common defects of the selected components.
- Assess the component condition based on defects with the use of the Analytic Hierarchy Process (AHP) for weights, Fuzzy Canonical Operation for defect evaluation and the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) for the aggregation.
- Assess the station and tunnel condition index with the use of the Analytic Network Process (ANP) for weights and the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) for the aggregation.
- Assess the subway line and network condition index with the implementation of the systems reliability approach.
- Design component deterioration curves with the use of Weibull analysis.
- Construct station and tunnel deterioration curves by applying the condition assessment methodology for the future component states as resulted from the component deterioration curves.
- Construct subway line and network deterioration curves.

Data for the determination of components and defects relative importance weights are collected through on-line surveys completed by subway experts. A website and an on-line survey are created to facilitate the data collection process. The developed methodology is implemented on a sub-network of Athens, Greece Metro System and the results from its first application are presented. The outcomes of the case study are compared with existing ones as found on literature for validation purposes. Finally, the entire developed methodology is incorporated in a user-friendly computerized automated tool in order to be able to be utilized fast and reliably from transit authorities and other interested parties.

1.5 Thesis Organization

This thesis comprises of seven chapters:

Chapter 1 briefly introduces this research by providing a background, the definition of the research objectives and a quick description of the methodology.

Chapter 2 provides an extensive literature review relevant to the scope of this research. It starts by exploring the current methodologies utilized in subway infrastructure performance evaluation by transit authorities and models found in the research area. The review continues by examining condition rating models in other types of infrastructures as well as deterioration models. The different mathematical approaches implemented so far in similar models are studied, namely Markov Chains and Weibull for deterioration models, Multi-criteria Decision Making (MCDM) techniques including the Analytic hierarchy Process (AHP), the Analytic Network Process (ANP), the Technique for Order Preference by Similarity to Ideal Solutions (TOPSIS) and the Fuzzy Canonical Operation. The Reliability approach for network performance models is also exploited. In addition, different researches and models are studied to identify subway components and relevant defects.

Chapter 3 explains analytically the developed models. It consists of three separate parts. First, the subway network components and defects are identified. Then the condition assessment model follows which starts from the component level where the evaluation is done based on defects and continues to the station/ tunnel, subway line and network level. The AHP, ANP, a customized version of TOPSIS and systems reliability theories are utilized. Finally, the condition prediction model is illustrated where deterioration curves can be constructed with the use of Weibull analysis.

Chapter 4 entails the data collection methodology and process. Data for the evaluation of relative importance weights are collected through an on-line questionnaire. The survey and the website that was created to host the survey are presented. An analysis of the responses is displayed.

Chapter 5 demonstrates the model implementation. Weights are calculated and the results are discussed. The model is applied into a sub-network of Athens, Greece subway system. Condition indexes are calculated and deterioration profiles are designed for the examined system. The case study results are compared with existing researches for validation purposes.

Chapter 6 contains the description of the developed software, the so-called "STREM Automated Tool". It includes snapshots of the computer application along with guidelines for potential users.

Chapter 7 is the final chapter of this thesis and includes the conclusions, contributions of this research, limitations and recommendations for future work.

2 Literature Review

2.1 Overview

In this chapter a comprehensive literature review related to this research is provided. Figure 2.1 shows a diagram of the explored literature for better understanding due to the extent of this research and the amount of information required.

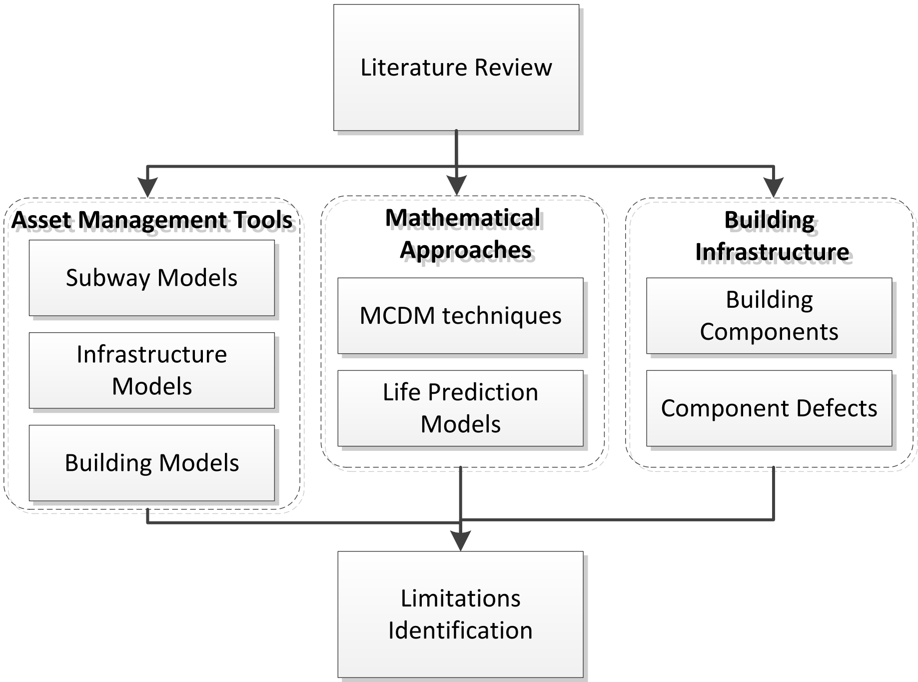


Figure 2.1 Literature Review Flowchart

In section 2.2, an overview of the existing methodologies utilized by major transit authorities for the performance evaluation of their subway assets is provided and discussed. Following in section 2.3, a quick reference to condition rating models of other types of infrastructures is presented. It also supplies a review of the techniques used for deterioration models and discusses the method used in this research. The network performance measurement method of systems reliability is illustrated in section 2.4 and an analytical description of the implemented mathematical approaches and multi-criteria decision making techniques is done in section 2.5. The literature review chapter then continues with a review of building components and hierarchies of them and the relevant defects of each component type (section 26). Finally this chapter concludes (2.7) with the identification of the limitations uncovered from the examined literature.

2.2 Subway Transit Authorities – Current Approaches

2.2.1 Montreal

The Montreal Metro system is operated by the "Société de Transport de Montréal". The network started its operation in 1966, thus it is already counting more than 50 years of life. Consequently, the transit authority is facing extensive infrastructure deterioration issues. The maintenance and repair planning policies are done by the "planification team". The basis of the planning is the regular inspections for each type of service or infrastructure of stations and tunnels by the relevant personnel, such as mechanical, electrical, building technicians etc. For projects of larger magnitude, the complete inspection process is assigned to external consultants (Semaan, 2006). In the 90's, the first large scale project related to subway station renovation took place, the so-called Reno-Stations, that included all the stations built in the first phase of the metro operation. The project was continued at 2005 called "Reno-Stations II" dealing with the restoration of the remaining stations. In parallel, another program, which is still continuing about the renovation of service systems such as escalators and communications systems was held and is called “Reno-Systemes” (STM, 2012). Although it is obvious from the extent of renovation works taking place, that a standard condition assessment process is a necessity, no comprehensive models for stations, tunnels or the entire network assessment are utilized. On the contrary, STM is evaluating the current infrastructure state at the component level and based on a simple 1 – 5 scale. The decisions for the stations to be included in the renovation plans were founded on the inspection reports and the age of the stations.

2.2.2 Athens

Athens’ metro system is very new in the world and is counted as a high-end contemporary transit project in terms of architecture, historical significance and community involvement (Attiko Metro SA, 2012). As stated above, the subway system is relatively new, it began operation in 2000; hence the transportation organization is not yet encountering the urgency of developing an advanced infrastructure performance rating model to assist in the maintenance and repair planning process. The transit authority is entailed of distinct departments (structural, communications, track work and power supply) and each one complies with the inspection and maintenance manuals. They conduct customer satisfaction related surveys annually including factors like schedule accuracy and cleanliness of stations and they estimate the Customer Satisfaction Index (CSI) and the European Passenger Satisfaction Index (EPSI). In addition, the track-work division performs a ranking of its performance according to the European Foundation of Quality Management (EFQM) (Athens Urban Rail Transport SA, 2013).

2.2.3 London Metro System

The “London Underground” is operated by Transport for London. They are among the first transit authorities to use some sort of methodology for the evaluation of their infrastructure. They developed a measure factor called Key Performance Indicator (KPI) that was applied on metro stations (Tolliver, 1996). The basis of this method is the feedback from customers on surveys about the condition of stations. The evaluation was done on the following set of criteria:

a) Cleanliness
b) Information Services
c) On-trains information, station services (accessibility, ticketing options, platform)
d) Safety and security
e) Train services (comfort, schedule, trip time, crowding)
f) Staff

Passengers are evaluating on 0 – 10 scale 23 different items with respect to the above listed factors. The KPI is counted as the average score of each evaluation multiplied by 10 in order to have the index in 0 – 100 scale (Abu-Mallouh, 1999).

2.2.4 California Train System

CalTrain transit system is one of the oldest in North America. Due to the extensive aging of its infrastructure, a station evaluation model was designed in the 1990's. Stations were ranked in a 1 (excellent) – 5 (poor) scale based on the following criteria:

a) Accessibility of the station
b) Location of the station and amenities
c) Parking availability
d) Connectivity with other modes of transportation
e) Appearance and cleanliness
f) Structural condition
g) Information services
h) Ticket vending machines
i) Security
j) Safety

Based on this evaluation, the Joint Power Board proceeds to the station selection for rehabilitation (Abu-Mallouh, 1999). Although this method includes some structural aspects, it is not a pure infrastructure condition assessment model since it includes factors of various natures. It is also limited to the evaluation of stations.

2.2.5 New York City Subway Network

The Metropolitan Transit Authority - New York City Transit (MTA NYCT) operates the subway system of New York City. It also is one of the oldest systems facing extensive deterioration. A point allocation system was implemented in order to evaluate stations to be prioritized for rehabilitation (Abu-Mallouh, 1999). The rating was done according to the following:

a) Structural condition
b) Daily usage
c) Felonies
d) Terminal station
e) Intermodal American Disabled Agreement
f) Automatic Fare Control
g) Security of outside funding
h) Developer funding potential
i) Point of interest

Each factor could be assigned up to a maximum number of points with a) and b) been the criteria that can record the highest points. The summation of the collected points for each station was an indication of the station condition and need for rehabilitation. This method is only limited to stations and considers many factors outside the interest of building condition assessment.

2.2.6 Washington D.C.

Washington Metropolitan Transit Authority (WMATA) has also been dealing with the overall performance of the metro network including some building services parts. They calculate Key Performance Indicators as a part of their annual “Vital Signs Report” (WMATA, 2013). Different factors are evaluated such as:

a) Rail Fleet Reliability
b) Escalator System Availability
c) Elevator System Availability
d) Customer Injury Rate
e) Employee Injury
f) Crime Rate
g) Customer Satisfaction

The KPI is calculated as a percentage mostly of achieved activities over planned. This methodology focuses on many different factors and does not produce any indexes for the building performance of the entire network.

2.2.7 Previous Research on Subway Systems

The Model for Station Rehabilitation Planning (MSRP) was developed in accordance with MTA NYCT in an attempt to enhance the previous implemented process by the transit authority (Abu-Mallouh, 1999). The MSRP is using the same point allocation system on the same factors provided by the authority. With the implementation of the AHP, weights are determined for the studied stations and then Integer Programming is used as an optimization technique for budget allocation of stations to be rehabilitated. A station with a certain range of weight and budget is qualified for rehabilitation. The MSRP model is mainly a budget allocation model that again only focuses on stations, which it evaluates, based on a variety of criteria, physical and social. It also does not include the deterioration issue at all.

A condition assessment model called "SSDI" was developed and implemented in the Montreal Metro system (Semaan, 2006). As its name claims, it is a methodology focusing on stations. The hierarchy of a typical station is constructed including operational criteria and sub-criteria as seen in Figure 2.2. The Analytic Hierarchy Process (AHP) is used for the definition of relative importance weights of criteria and sub-criteria.

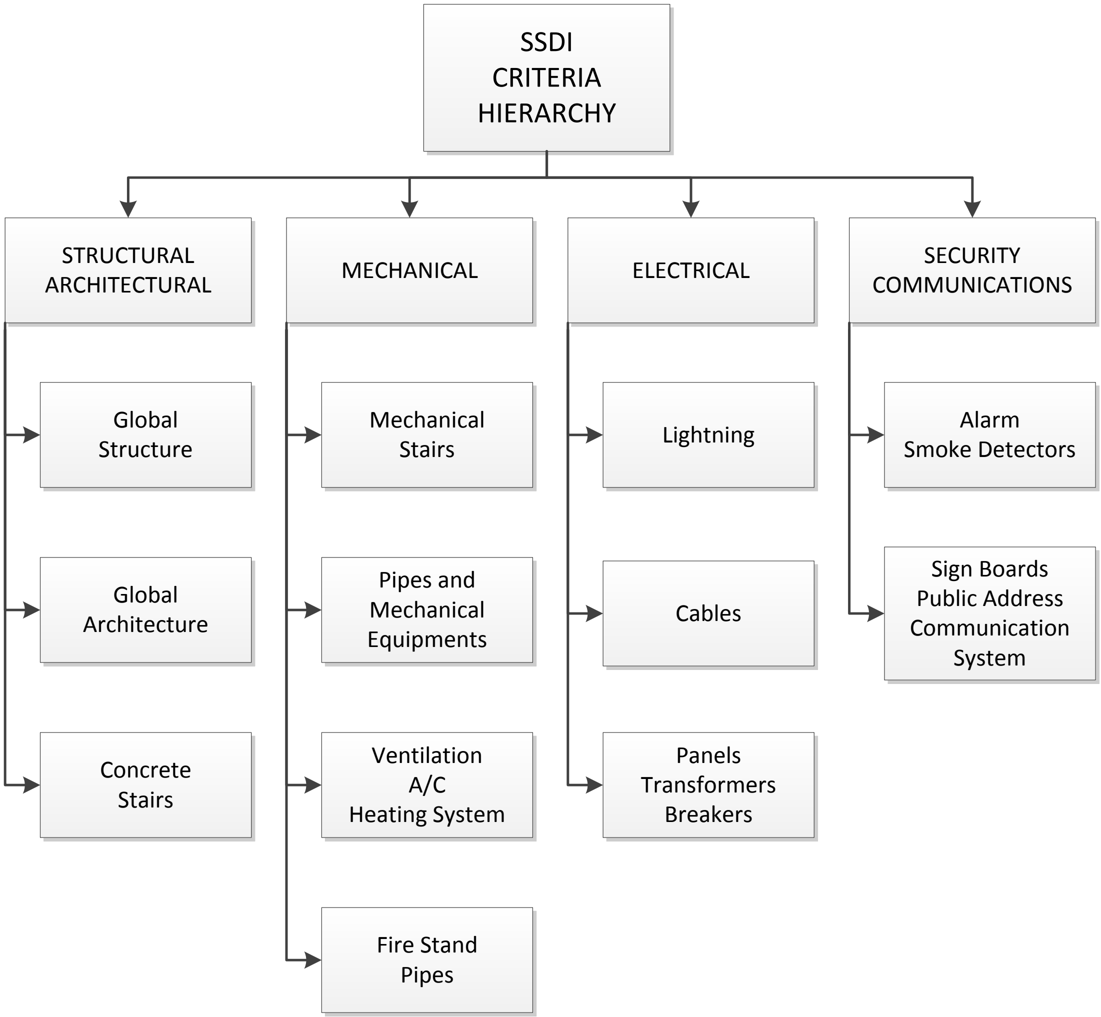


Figure 2.2 SSDI Station Hierarchy

The sub-criteria are then evaluated for their current performance based on a simple 1-5 scale that is seen in Table 2-1.

Table 2-1 SSDI Criteria Evaluation Scale

Scale	Description
1	Critical Condition
2	Deficient Condition
3	Poor Condition
4	Acceptable Condition
5	Good Condition

Table 2-2 SSDI Condition Scale

SDI	Description	Deterioration Level (%)	Proposed Action
8<SDI<10	Good	<17% Structural or, <12% Communications or, <15% Electrical or, <14% Mechanical	Long Term: *Expertise < 2 years *Physical < 5 years Review in 2 years
6<SDI<8	Medium	>17% & <23% Structural or, >12% & <17% Communications or, >15% & <21% Electrical or, >14% & <21% Mechanical	Medium Term: *Expertise < 1 year *Physical < 2 years Review in 1 year
3<SDI<6	Deficient	>23% & <35% Structural or, >17% & <26% Communications or, >21% & <33% Electrical or, >21% & <34% Mechanical	Short Term: *Expertise < 6 months *Physical < 1 year Review in 6 months
0<SDI<3	Poor	>41% Structural or, >30% Communications or, >38% Electrical or, >40% Mechanical	Immediate: Physical Intervention Now

An aggregation of weights and scores takes place with the implementation of the Preference Outranking Method of Enrichment Evaluation (PROMETHEE) and a final condition index for each station is calculated with the use of the Multi-Attribute Utility Theory (MAUT). The model also proposes a corresponding scale for the state of the infrastructure based on the calculated result as well as suggested intervention actions (Table 2-2).

This was the first attempt of representing the condition of any subway infrastructure with a single number, the Station Condition Index. The SSDI model is limited to subway stations and is not further applicable to tunnels, lines and network. Also, the condition assessment is done based on visual evaluation of the different station criteria/ functions without examining the presence of any defects and there is no information about the station's deterioration progress in time.

Another model that was developed and applied in the Montreal metro system, the so-called "SUPER Model" (Semaan, 2011) is handling the issue of structural performance of subway systems. The model assesses the condition of structural components based on defects of stations, tunnels and auxiliary structures. The different defects are weighted with the AHP. An evaluation of each defect is done based on a simple 0-5 scale. The combination of weights and scores to form a component condition index is done with the multiplicative form of the MAUT. From the level of the component, the systems reliability theory is implemented for the upper levels of the hierarchy. First the stations, tunnels and auxiliary structures, continuing the subway lines and finally the network are evaluated. The proposed subway network structure is seen in Figure 2.3.

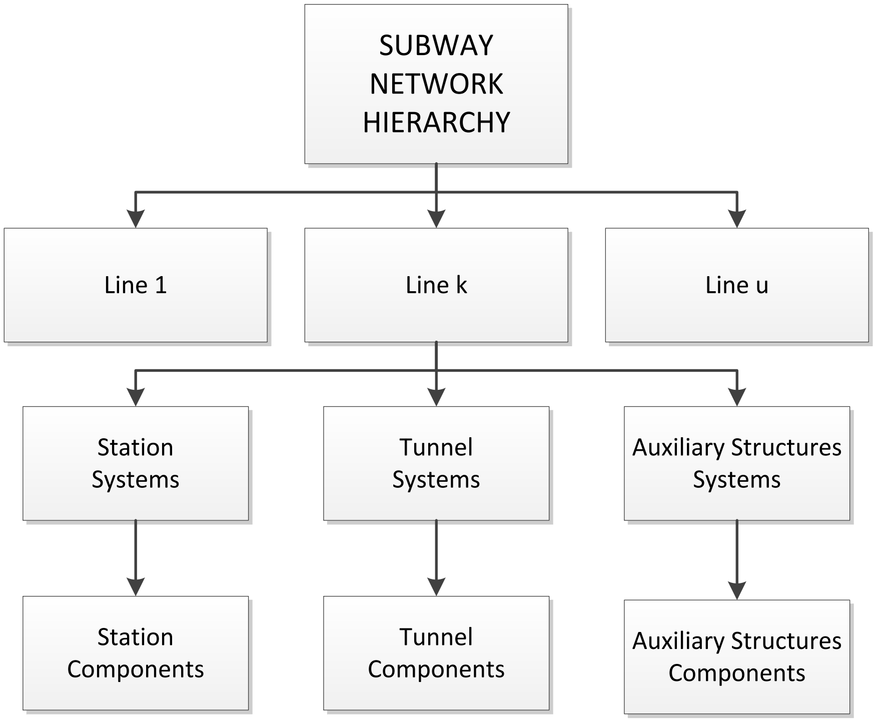


Figure 2.3 SUPER Model Network Hierarchy

The SUPER Model also provides performance prediction curves for all the levels of the subway network hierarchy. The deterioration models are drawn with the use of Weibull functions. The major limitation of the SUPER model lies to the fact that it is solely assessing the structural performance of subways and also does not consider any uncertainties in the defects evaluation process.

A model focusing on the maintenance and rehabilitation planning of public infrastructure was also applied in the Montreal subway system, the "MRPPI" (Faraan, 2006). This research is based on life-cycle cost analysis of building components. It utilized Markov Chains theory and forms transition probability matrixes in order to estimate the deterioration of the components. A genetic algorithm approach is implemented to minimize the life cycle cost of the examined component considering intervention actions such as preventive maintenance, repair and rehabilitation. The MRPPI model requires a very large amount of data input since it is using Markov theory making it somehow dysfunctional. Another limitation is that it is implemented on a single structural element of the subway infrastructure (station slab) and cannot be applied on the entire network.

A model for the evaluation of the functional condition of subway stations was developed and applied for Athens Metro systems (Kepaptsoglou et al, 2012). Stations were divided into operational criteria abiding to each department of the transit authority as seen inFigure 2.4.

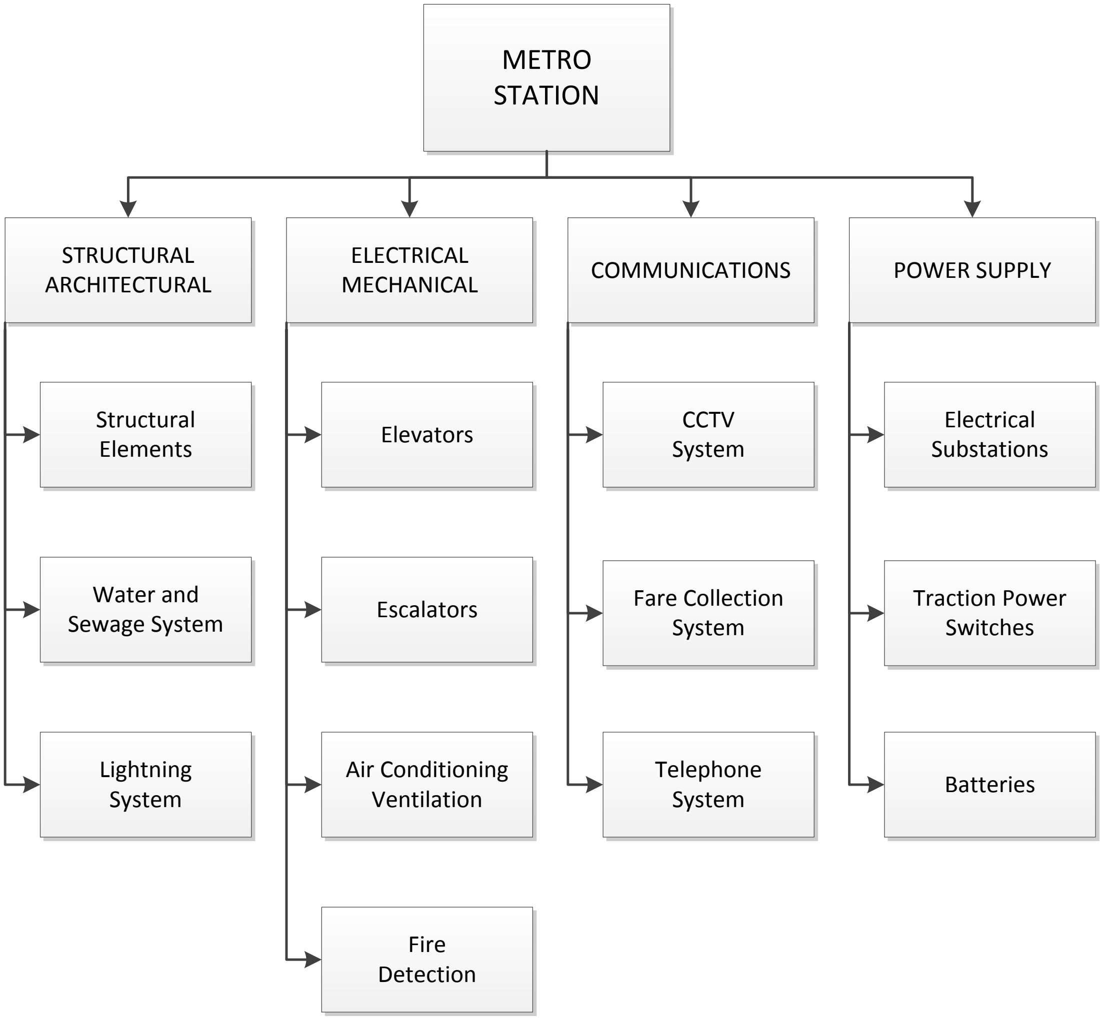


Figure 2.4 MCI Station Functional Diagram

The different criteria and sub-criteria are weighted for their importance to the operation of a station with the use of AHP and Fuzzy AHP. Every sub-criterion is evaluated directly from the transit authority on a 0 – 5 scale and then weights and scores are aggregated with the additive form of MAUT to form the so-called MCI or Metro Condition Index. Again this research is limited only to the evaluation of stations and is not applicable to the network level. Although it is capturing the ambiguities of expert opinions when determining the criteria weights, it does not consider the uncertainties in factor evaluation, which is done on an abstract basis and not based on defects.

In an attempt to improve this model, in another study the authors implemented the Analytic Network Process to attain the interdependencies among the criteria (Gkountis and Zayed, 2013). The same 0 – 5 scale is used and the additive MAUT is implemented to form an index depicting the station's condition. The shortcomings of this study remain, although the use of the ANP adds a new dimension to the problem, which is the interdependency among criteria.

A study called "Evaluating, Comparing and Improving Metro Networks" (Derrible and Kennedy, 2010) was recently done, examining subway systems in the network level from the side of system efficiency and ridership improvement. A network design model (graphic model) is prepared and 3 main indicators are calculated, namely a) coverage, b) directness and c) connectivity. The calculation of these factors based on variables such as ridership, covered area, number of lines and possible transfer options allows for the measurement of the network performance and can be used for comparison purposes among different subway networks. An application of the study has been done on the Toronto Metro system. Although this research deals with subways as a network, it does not focus on the building infrastructure and does not provide any condition or deterioration assessment options.

A framework for subway maintenance called "Maintaining Subways Infrastructure Using BIM" was developed recently (Marzouk and Abdel Aty, 2012). It is proposing a Building Information Modeling (BIM) model for subways including asset management indicators for a) structural integrity, b) mechanical systems, c) HVAC systems and d) electrical system and user-related indicators. The model only provides a platform and a proposed BIM flowchart without continuing and defining the proposed indicators, but it considers them as ready inputs to an integrated BIM/Asset management model.

2.3 Infrastructure Condition Assessment and Deterioration

Although a lack of models focusing on transit systems and especially on subways has been identified by the literature, a significant amount of research has been done for other type of infrastructures such as bridges (PONTIS, Thompson et al. 1998, Golabi and Shepard, 1997), pavements (Butt et al. 1987, PAVER, Shahin, 1992), pipelines (Chungtai and Zayed, 2008, Al-BArqawi and Zayed, 2006) and buildings (TOBUS, Flouretzou et al. 2002, Brandt and Rasmussen, 2002, RECAPP, 2006, Eweda et al. 2013, Ahluwalia, 2008). Especially in the case of bridges and buildings, the issue of deteriorating infrastructure has been handled in a national level (since they are mostly public owned and operated structures) by the USA (PONTIS, NBIS for bridges, BUILDER) and Canada (MTO BHI, SGSQ) adapting guidelines, specifications and developing software for the implementation of the developed methods.

The provision of the future condition of infrastructure, which is based on the degradation progress in time, is a very important aspect in any asset management tool since it is enhancing the maintenance, repair and rehabilitation planning (Ahluwalia, 2008). By default over the course of its lifespan, a component will deteriorate with the passing of time and usage until it reaches a certain point where it can no longer be considered as operational due to (Hudson et al. 1997):

a) Physical deterioration
b) Poor performance
c) Functional obsolescence
d) Unacceptably increased operating cost

Several methodologies have been used to predict future performance or deterioration such as regression models, curve-fitting models, Markovian models and reliability-based models (Elhakeem, 2005).

2.3.1 Markovian Models

Perhaps the most commonly used approach in deterioration models is the Markovian approach and has been used in a wide range of infrastructures (Karlaftis, 1997). The Markovian property or lack-of-memory property describes that the probability of any future state is completely independent of the current or past states (Farran, 2006). The heart of the Markov Decision Process (MDP) is the Transition Probability Matrix. After defining standard states, the probability of transition from one state to the next one is needed. Here lies the major disadvantage of this technique, its need for a very large amount of data input in order to define these transition probabilities whose number grows depending on the number of the discrete states. From the transition probability matrix, with the implementation of a sequence of matrix calculations, the future condition can be retrieved (Baik et al. 2006).

2.3.2 Weibull-Based Models

Weibull models have been widely implemented in many applications of different natures and for solving a variety of problems from many different disciplines (Jardine and Tsang, 2013). Every human-made product and system, from simple products to complex structures, has certain unreliability and they deteriorate with time until they ultimately fail (Murthy et al. 2004). The typical life of a product or component can be described by the following equation:

$$f(t) = \frac{\beta}{\eta}\left(\frac{t-\gamma}{\eta}\right)^{\beta-1} e^{-\left(\frac{t-\gamma}{\eta}\right)^{\beta}} \quad for\ t > \gamma \tag{2.1}$$

Where:

β = shape parameter

γ = location parameter

η = scale parameter

t = time

From this model, the cumulative Weibull distribution function can be defined and finally based on that the Weibull reliability function is drawn which is seen in equation 2.2.

$$R(t) = 1 - F(t) = e^{-\left(\frac{t-\gamma}{\eta}\right)^{\beta}} \tag{2.2}$$

According to building condition prediction models (Grussing et al. 2006) the Weibull reliability function can be used for the purposes of building components life cycle assessment and is transformed into the following equation:

$$CI = A \times e^{-\left(\frac{t}{\beta}\right)^{\alpha}} \tag{2.3}$$

Where:

CI = component condition index

A = initial condition

t = time in service

α = degradation factor

β = service life adjustment factor

2.4 Network Performance – Reliability Approach

With reference to the previously examined literature, many methodologies have been identified that focus on the condition of infrastructure components or sub-divisions such as subway stations, pipelines or bridges. The great challenge is how to assess the condition in a network level. Few available researches have dealt with this subject for subway networks (Semaan, 2011), bridges (Ghodoosi et al, 2013) and pipeline networks (Salman, 2011). The systems reliability approach has been applied for this purpose. Reliability is defined as the ability of a component or system to function under specific conditions for a specified period of time (Bertsche, 2008). In another explanation, reliability can be defined as the probability of failure (Salman, 2011). Systems can be described in two forms, as systems in series or parallel systems.

A system is considered to be in series when a failure of one of its components causes the complete failure of the entire system. Mathematically this is represented by the following equation:

$$p_s = \prod_{i=1}^{n} p_{si} \tag{2.4}$$

$$p_f = 1 - \prod_{i=1}^{n} (1 - p_{fi}) \tag{2.5}$$

Where:

p_s = probability of safety and

p_f = probability of failure

On the other hand, a system is in parallel when in the occasion of a component's or sub-system's failure then the operation of the entire is not affected because there are alternative ways of service or function. The next equation describes the parallel systems:

$$p_f = \prod_{i=1}^{n} p_{fi} \tag{2.6}$$

$$p_s = 1 - \prod_{i=1}^{n} (1 - p_{si}) \tag{2.7}$$

2.5 Multi-Criteria Decision Making

"Decision making is the study of identifying and choosing alternatives based on the values and preferences of the decision maker. Making a decision implies that there are alternative choices to be considered, and in such a case we want not only to identify as many of these alternatives as possible but to choose the one that best fits with our goals, objectives, desires, values, and so on" (Fulop, 2005).

Generally, in the Decision Making research area, some discrete steps have to be made to get to the desirable result (Harris, 1998, Baker et al. 2002). These are:

1. Decision Problem Identification
2. Goal establishment
3. Criteria/factors identification
4. Rules establishment or choice of the appropriate MCDM tool that aggregates best the criteria with the goal
5. Results validation

2.5.1 The Analytic Hierarchy Process (AHP)

The Analytic Hierarchy Process (AHP) was developed in Wharton School of Business in 1980 by Thomas L. Saaty (Saaty, 1980). It is one of the most powerful and widely used techniques for extracting priorities and weights in the Multi-criteria Decision Making (MCDM) area.

The main axioms of the AHP can be encapsulated in the following:

- The decision problem is structured in a hierarchical form where the goal is divided into criteria and respecting sub-criteria (Figure 2.5).
- An importance scale is provided in order to allow decision makers to compare among the factors affecting the decision problem (Table 2-3).
- A pairwise comparison of all the elements of the decision problem is done with the use of the previous importance scale (Figure 2.6).

- Priorities or weights are extracted based on these pairwise comparisons with the use of the AHP mathematics.

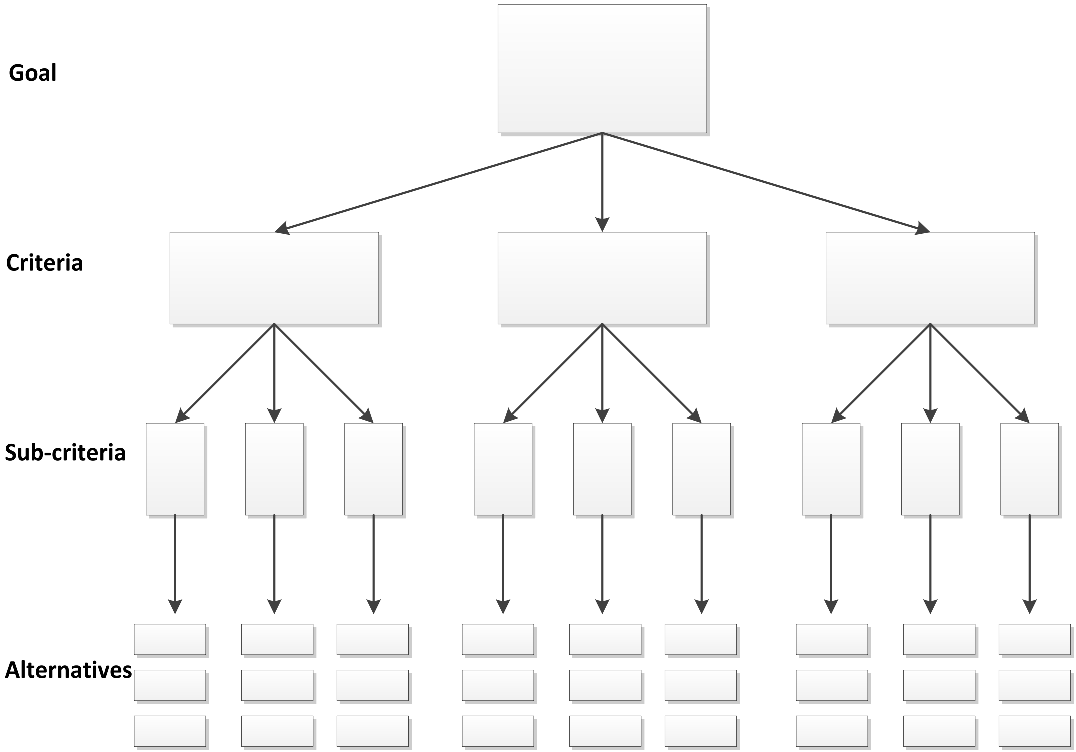


Figure 2.5 Hierarchical Structure of the Decision Problem

Table 2-3 Saaty's Fundamental Scale

Fundamental Scale	
1	equal importance
3	moderate importance
5	strong importance
7	very strong importance
9	extreme importance
2,4,6,8	intermediate values
Reciprocal values for inverse comparison	

$$A = \left\{ \begin{array}{c|c|c|c|c} & 1 & 2 & 3 & 4 \\ \hline 1 & 1 & a_{12} & a_{13} & a_{14} \\ \hline 2 & 1/a_{12} & 1 & a_{23} & a_{24} \\ \hline 3 & 1/a_{13} & 1/a_{23} & 1 & a_{34} \\ \hline 4 & 1/a_{14} & 1/a_{24} & 1/a_{34} & 1 \end{array} \right\}$$

Figure 2.6 Pairwise Comparison Matrix

The weight calculation process is based on the information input in the pairwise comparison matrix. A matrix has to be completed for each level of the decision problem. For instance, sub-criteria are compared between each other with respect to the parent criterion and criteria are compared with respect to the goal. The following equations illustrate the intermediate weight calculation steps:

From matrix A:

1) $S_j = \sum a_{ij} \;, \forall\, j$ (2.8)

2) $a'_{ij} = \frac{a_{ij}}{S_j}$ (2.9)

3) $W_{a_{ij}} = \frac{(\sum a_{ij}')}{n} \;, \forall\, i \;\; where\; i = 1,2,\ldots,n$ (2.10)

4) $\sum W_{a_{ij}} = 1.0$ (2.11)

This is known as the geometric mean method of extracting weights using the AHP. Another known method which is not considered in this research though, is the method of the eigenvector. The AHP also allows for inconsistency in the pairwise comparison process and sets threshold of acceptable inconsistency. In this research, the consistent-type matrixes are designed. This means that weights are calculated indirectly for some sub-criteria affecting the same criterion. In example, by knowing the preference of A over B and A over C, the preference of B over C can be safely estimated without actually having to ask this question to the decision maker. Hence, the need of calculating consistency ratios is waived.

2.5.2 The Analytic Network Process (ANP)

The Analytic Network Process (ANP) came as an improvement of the formerly introduced AHP (Saaty, 2001). A main assumption of the AHP is that decision elements are independent form sub-elements or any decision factors in a different level of the hierarchy. The decision problem can now actually take the form of a network (Figure 2.7). Clusters and nodes inside clusters are taking the place of the hierarchy levels. This form allows any type of dependency between elements of different clusters and also interdependency among nodes in the same cluster.

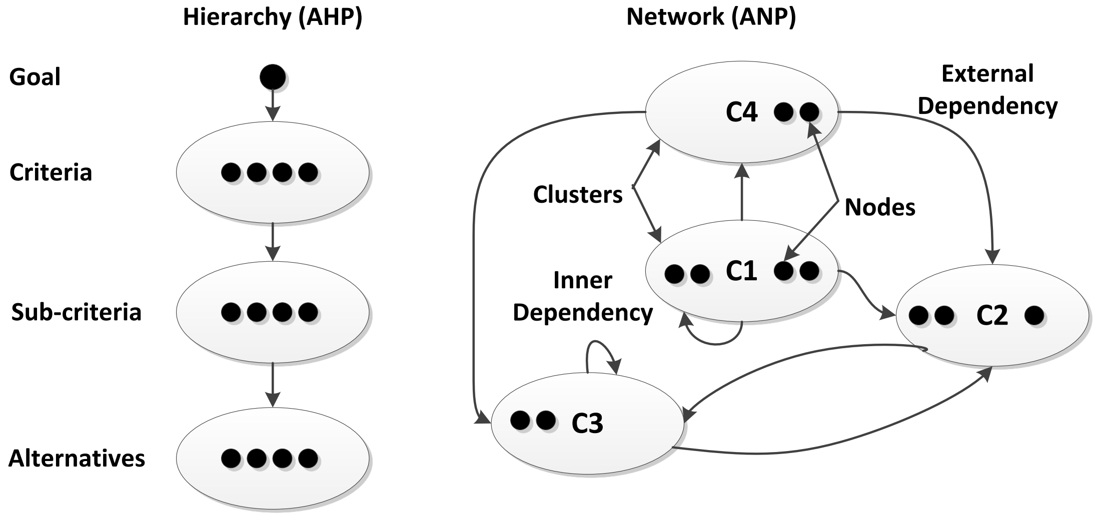


Figure 2.7 Decision Network vs. Decision Hierarchy

The basis of the calculation is the pairwise comparison matrixes of the studied elements with respect to the control criterion. The fundamental scale (Table 2-3) is used to complete such a matrix. Following the same process as in AHP, the weights of elements or nodes for each such comparison matrix are calculated. These are now called local priorities or local eigenvectors.

In order to synthesize the information collected from all the comparisons, a super matrix is constructed. The super matrix is a matrix that includes all the decision clusters and nodes and is filled with the local priorities derived from the previous step. At this moment, the super matrix is called un-weighted super matrix. The next step is the weighted super matrix where all elements or nodes are weighted based on their control criterion, which means the local priorities are multiplied with the relevant cluster weights. The last step is the composition of the limiting super matrix, which is the product of the constant raising of the weighted super matrix into powers until it converges. The final weights derive from the limiting super matrix after normalization based on the respecting clusters and nodes structure.

2.5.3 The Technique for Order Preference by Similarity to Ideal Solution (TOPSIS)

The Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) is a Multi-criteria Decision Making technique used for alternatives ranking (Yoon, 1980, Hwang et al. 1981). The fundamental concept of TOPSIS is that the best of a set of alternatives should accomplish both minimum distance from the ideal solution and maximum distance from the negative-ideal alternative. This is one major advantage of TOPSIS, since it provides 2 control points. The mathematics of the technique is described in the following steps:

1) Assume a typical decision problem D, with n alternatives (A_i), m decision attributes (or factors), X_{ij} is the evaluation of every alternative for the respective attribute and W_j are the weights of each attribute as seen in equation 2.12.

$$D = \begin{array}{c} \\ A_1 \\ A_2 \\ \vdots \\ A_n \end{array} \begin{array}{c} \begin{array}{cccc} W_1 & W_2 & \dots & W_m \end{array} \\ \begin{bmatrix} X_{11} & X_{12} & \cdots & X_{1m} \\ X_{12} & \cdots & \cdots & \vdots \\ \vdots & \ddots & \ddots & \vdots \\ X_{n1} & \cdots & \cdots & X_{nm} \end{bmatrix} \end{array} \tag{2.12}$$

2) The decision matrix is then normalized with the use of the next equation.

$$r_{ij} = \frac{\mathrm{Xij}}{\sqrt{\sum_{i=1}^{m} Xij^2}} \tag{2.13}$$

Where, r_{ij} are the normalized attribute values.

3) The weighted normalized decision matrix is the next step, where the normalized attribute values are multiplied with the relative attribute weight.

$$V_{ij} = W_j \times r_j \tag{2.14}$$

Where V_{ij} are the weighted normalized attribute values

4) The next step is the selection of the positive ideal and negative ideal solutions.

$$A^+ = \{(maxV_{ij} | j \in J), (minV_{ij} | j \in J')\} = [V_1^+, V_2^+, \dots, V_m^+] \tag{2.15}$$

and

$$A^- = \{(minV_{ij} | j \in J), (maxV_{ij} | j \in J')\} = [V_1^-, V_2^-, \dots, V_m^-] \tag{2.16}$$

Where, J refers to typical benefit type attributes and J′ to typical cost type.

5) Afterwards, the separation measures are calculated.

$$S_i^+ = \sqrt{\sum_{j=1}^{n} (V_{ij} - V_j^+)^{\ 2}}\ , \ i = 1,2, \dots, m \tag{2.17}$$

Where, S_i^+ is the ideal separation and

$$S_i^- = \sqrt{\sum_{j=1}^{n}(V_{ij} - V_j^-)^{\,2}}\ ,\ i = 1,2,\dots,m \tag{2.18}$$

Where S_i^-, is the negative ideal separation.

6) The final step is the calculation of the Relative Closeness Coefficient, which the measure based on which the ranking of the alternatives is made. The alternatives with the highest C_i values are the better ones. The C_i ranges between 0 and 1.

$$C_{i=} \frac{S_i^-}{(S_i^+ + S_i^-)}\ ,\ 0 < C_i < 1,\ i = 1,2,\dots,m \tag{2.19}$$

TOPSIS is a powerful tool that has been used in the past in various studies on a wide range of decision making problems, such as the optimal power plant location selection (Chu, 2002 and Yong, 2006), web services selection (Lo et al, 2010), in supplier selection (Wang et al. 2009, Deng and Chan, 2011) and transshipment site selection (Onut and Soner, 2008).

One problem of TOPSIS is that the technique is dynamic in the sense that, the calculated coefficients are depending on the evaluation of existing alternatives and are subject to change upon the addition or extraction of alternatives. So, the finally calculated coefficient although resembles an index suitable for this research, it is not exactly fitting the objective. The technique needs to be customized in order to be implemented.

2.5.4 Fuzzy Extensions on TOPSIS

In an attempt to capture uncertainties in the evaluation of attributes in a decision making problem structured and solved with TOPSIS, a fuzzy approach for the representation of attribute values has been utilized by researchers in the past (Chu, 2002, Wang et al. 2009 and Lo et al. 2010). Scores are substituted by triangular fuzzy numbers (TFN) and the graded mean integration of TFNs as it is used in the canonical operation representation of fuzzy numbers (Chou, 2003) is used to extract crisp values out of the fuzzy sets. This process takes place with the following formula:

$$P(Y) = \frac{1}{6}(\mathrm{a} + 4b + c) \tag{2.20}$$

Where, Y(a,b,c) is a typical TFN with a been the minimum, b the most probable and c the maximum value the Y can get.

2.6 Building Infrastructure – Components and Defects

This research is focusing on the electrical and mechanical infrastructure of subway networks which has not been taken into account in many existing subway management models. This reality creates a great challenge since very limited information is available about subway electrical and mechanical components. As discussed extensively in the first part of the literature review, few methodologies exist about the condition assessment of metro facilities. Because of the more generic expert-based evaluation approach followed by Semaan (2006) and Kepaptsoglou (2012 and 2013) another round of research including the breakdown of typical building components is performed in an attempt to "borrow" knowledge from the building infrastructure research industry.

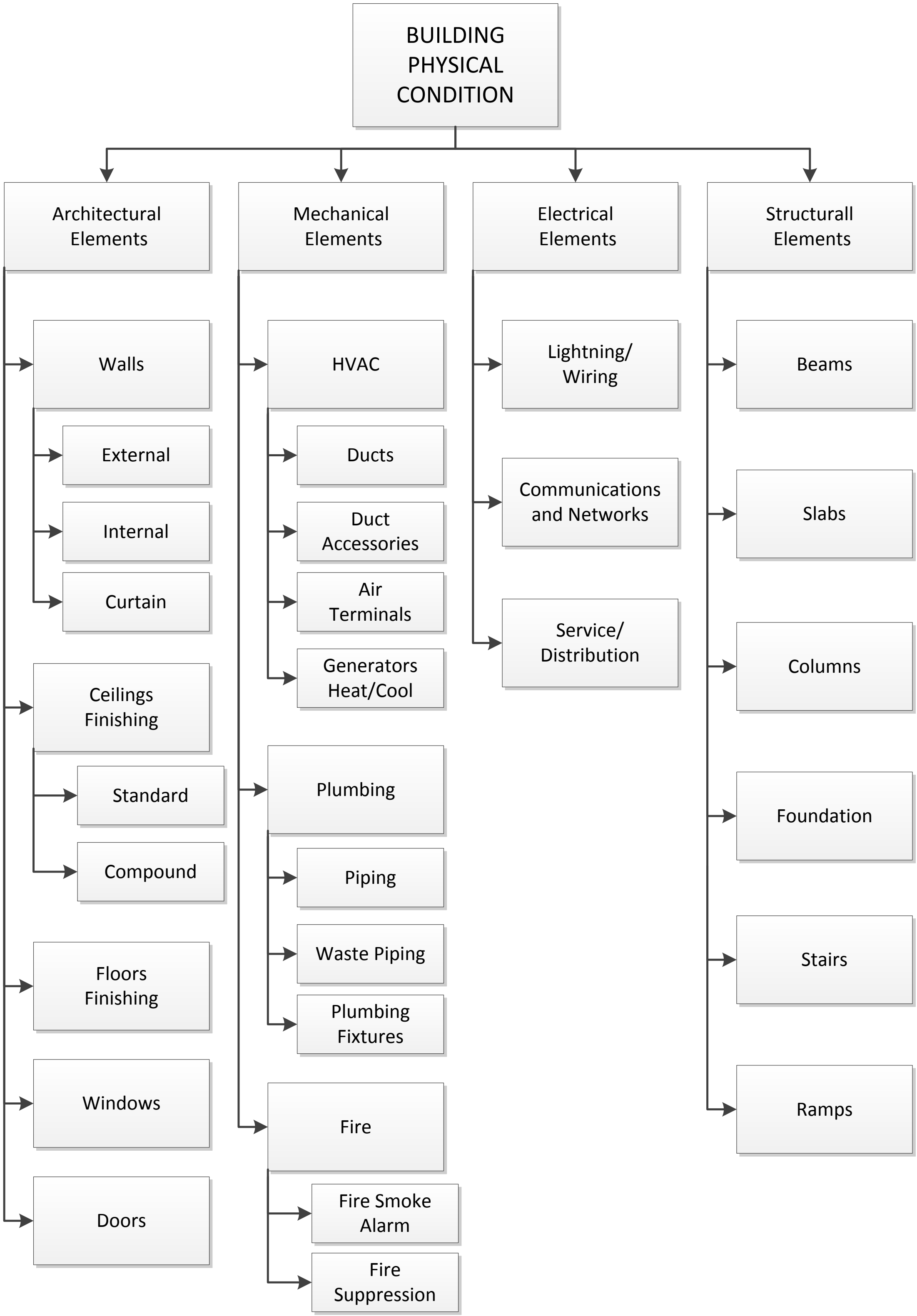


Figure 2.8 Building Electrical and Mechanical Components (Eweda, 2012)

Thanks to the abundance of building condition assessment models (Elhakeem, 2005, Eweda, 2012, Alhuwaila, 2008, BUILDER, 2002, Das and Chew, 2011), many condition assessment reports (ECS Mid-Atlantic LLC, 2010, CBCL Limited, 2007) on actual buildings and the UNIFORMAT breakdown structure, an extensive list of building components has been identified. The disadvantage of these resources -other than the obvious, that they are assessing building condition and not subway-related infrastructure- is the amount of components included. Builder proposes a structure of almost 150 components. A careful filtering needs to be made for the most suitable components to be selected. More discussion and the proposed hierarchy of components can be found in the methodology part of this thesis.

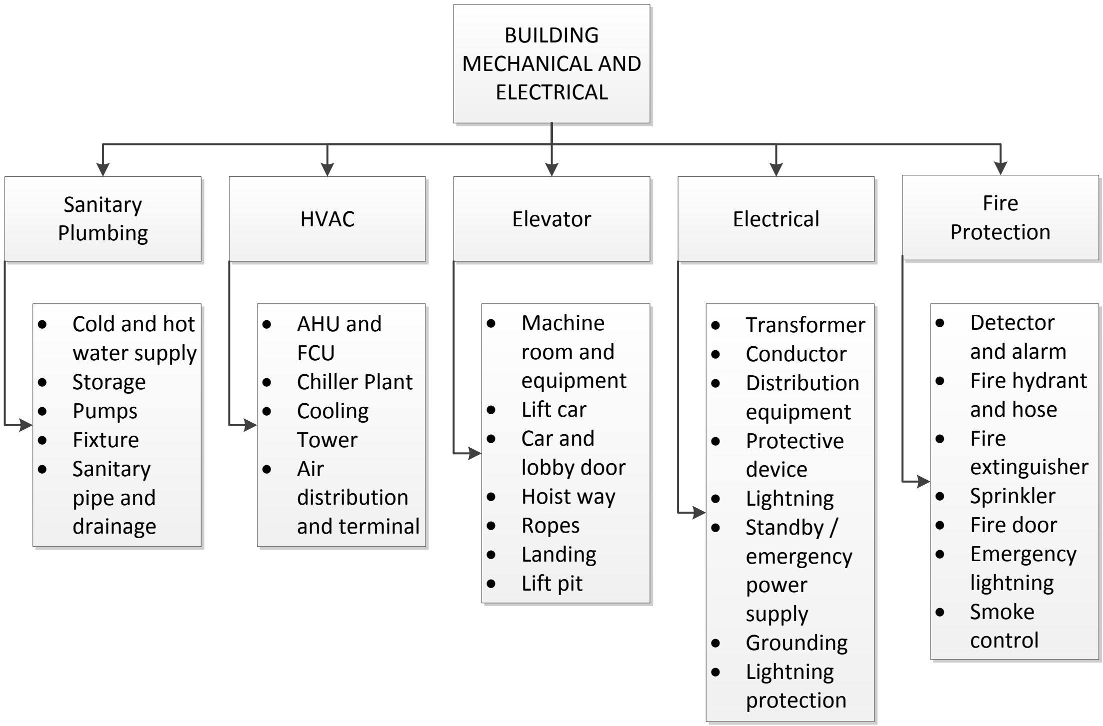


Figure 2.9 Building Components Hierarchy (Das and Chew, 2011)

Condition rating when done based on the presence and extent of actual defects eliminates subjectivity in component evaluation. A review of the defects affecting the state of electrical and mechanical infrastructure is conducted in order to identify the most suitable defects for the case of metro infrastructure. Again, due to the lack of defect-based condition rating models, a review of typical building defects is executed. The previously mentioned building condition assessment models such as BUILDER and RECAPP provide a list of deficiencies for each component. Researches can also be found including building defect-surveys (Chong and low, 2006). A building maintainability model recently developed provides a more condense description of defects (Das and Chew, 2011) as can be seen in Table 2-4 and Table 2-5.

In addition, many building evaluation reports from consultant companies can be found on the internet that describe the defects of each investigated component (ECS Mid-Atlantic, LLC 2010, CBCL Ltd 2007).

Table 2-4 Electrical and Mechanical Defects List

Components	Defects
Services (sanitary plumbing)	Pipe leakage Floor leakage Pipes corrosion Water ponding Staining
General electrical system	Short circuit Shock and electrocution Arc, spark Total power cut
Transformer	Vibration and noise Overheating Oil leakage Damaged insulation

Table 2-5 Electrical and Mechanical Defects (cont'd)

Components	Defects
Cable and Wiring	Mechanical damage Corrosion Damaged insulation Damaged electric box
Distribution equipment	Burnt mark on switchboard Noise/ spark No power at receptacle Loose switchgear
Lightning	Lamps flicker and frequent blow off Less light/ no light Damaged casing Overheating Overnoise
Emergency power supply	Generator noise, vibration and overheating Damaged insulation Generator Leakage No/ Delayed/ less power supply

2.7 Summary and Limitations

An extensive literature review was performed covering the current practices of subway condition assessment and deterioration modeling as well as the mathematical approaches used to handle such problems. According to this study’s findings, many limitations can be identified on the existing methods that transit authorities use for asset evaluation and on the actual subway condition rating models and on the mathematical techniques utilized in these models:

- Transit authorities do not deal with the task of condition assessment and usually assign inspection and condition evaluation to external consultants.

- The few models that are actually used by transit authorities include factors of various natures, irrelevant to the physical condition of subway infrastructure.
- Customer satisfaction surveys are the most prominent endeavors undertaken by Metro operators and provide performance indicators related to schedule accuracy, comfort, security and system’s attractiveness.
- Many researches do not provide an index-based representation of the infrastructure’s state; they rather end up in an infrastructure ranking for maintenance and rehabilitation.
- Many of the developed models focus only on subway stations’ infrastructure.
- Subway tunnels are most commonly not considered in the condition assessment process.
- Almost all models do not examine subway infrastructure from a network perspective but focus only in specific sub-divisions and components.
- Only one model has been so far has attempted to consider the deterioration of subway infrastructure and that is evaluating the structural performance of the network.
- The electrical and mechanical infrastructure of subway has not been taken into account in some models and deterioration models for that type of infrastructure were unable to be found.
- The majority of the developed techniques assess the condition based on expert opinions through the evaluation of components with a specified scale and do not apply a defect-based approach to eliminate subjectivity matters.

- Multi-criteria Decision Making tools that have been used for the purposes of asset management do not always comply with the characteristics of the project and might need customization in order to better fit the scope.
- Mathematical approaches in many cases require a considerable amount of data input which are not available for subways and are very complex to be implemented by transit authorities.

Considering the review of literature and all its above mentioned limitations, a need for the development of a new subway asset management tool can be identified. This tool should include structural, electrical and mechanical infrastructure aspects and evaluate the current state based on actual defects. Moreover, a condition prediction model should be developed in collaboration with the condition rating model, in order to produce infrastructure deterioration profiles, thus facilitating the maintenance, repair and rehabilitation planning and the budget allocation processes.

3 Research Methodology

3.1 Introduction and Outline

Transit systems, such as subways, are responsible for safely transporting millions of passengers daily. The issue of deteriorating infrastructure is becoming very crucial, especially in North America. Therefore, the need for improvement and restoration of the infrastructure's current state is growing. As it has been established from the literature review, limited research has been conducted on the topic of subway networks. Transit authorities most commonly are planning their maintenance, repair and rehabilitation works based on engineering judgment and decision makers' preference depending on the current circumstantial needs and budget allowances. This may provide a partial solution to the problem but in the long-term it might even hurt the entity of the network due to unbalanced treatment and capital mismanagement. Very few well-defined models are applied by certain transit authorities, covering their needs and understanding of subway performance. Similarly, in the research area, developed methodologies have been using ranking techniques for subway prioritization and only recently some studies are adapting an index-based subway condition depiction. Especially for the electrical and mechanical infrastructure of subways, although considered in some station-specific models, an extensive study on their condition and deterioration has not yet been located from the literature.

Due to these limitations, in this current research, a detailed defect-based condition assessment model for all the levels of subway networks (components, stations, tunnels, lines and network) is developed. The electrical and mechanical infrastructure is thoroughly examined and eventually integration with structural models is feasible for the holistic assessment of subway systems. Moreover, the suggested methodology facilitates the future performance prediction of subways through constructing the relevant deterioration profiles. The outcomes of this methodology can be of great value upon interpretation by transit authorities, assisting in the proper maintenance, repair and rehabilitation planning and in the more effective budgeting process.

The detailed flowchart of the proposed model can be viewed in Figure 3.1 and the undertaken steps are outlined in the following:

1) Identify the different subway network components and propose a hierarchy.
2) Assess the condition of subway infrastructure.
    a. Identify the common defects affecting the condition of components.
    b. Assess the component condition based on defects.
    c. Assess the condition in the station/tunnel level.
    d. Assess the condition in the line/network level.
3) Model the deterioration of subway infrastructure.
    a. Draw component deterioration profiles.
    b. Draw station/tunnel deterioration profiles.
    c. Draw line/network deterioration profiles.
4) Incorporate the developed methodology in an automated tool.

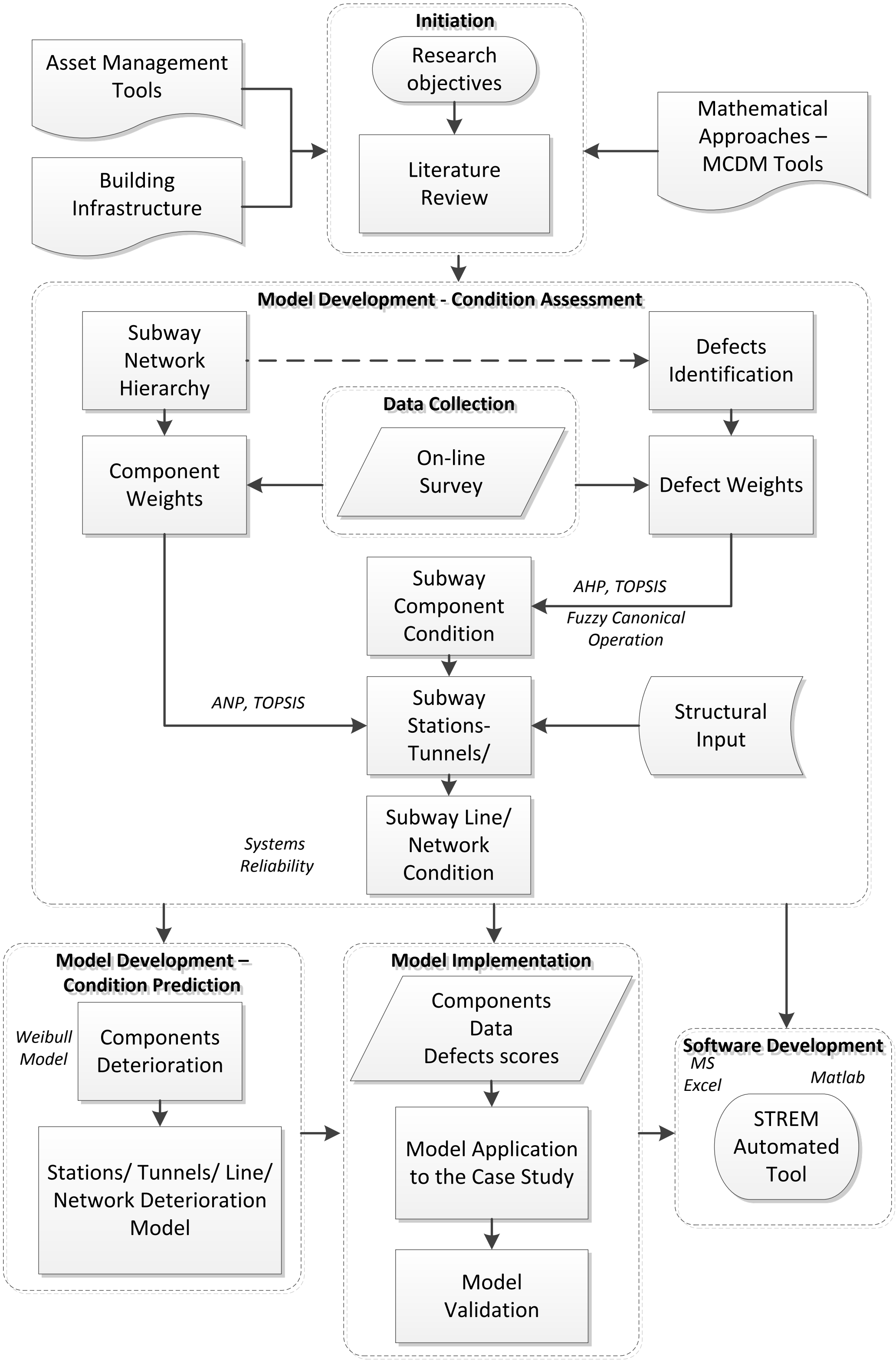


Figure 3.1 Detailed Methodology Flowchart

3.2 Literature Review

An extensive literature review was performed to familiarize with current practices, identify their shortcomings and build a new model by targeting these deficiencies and hence, contribute to the improvement of subway asset management area. The literature review covered three discrete categories that are listed below:

- Asset management tools, condition assessment models, deterioration models and network performance models implemented on subways or any other type of infrastructure.
- Mathematical approaches commonly utilized for the solution of such problems, including a deep insight in Multi-criteria Decision Making techniques.
- Building Infrastructure models and reports for the identification of a suitable components breakdown and the comprehension of their deterioration mechanisms and frequently observed defects.

Every item presented in the literature review part is evaluated based on the demands of the current research and its ability to contribute to the defined research objectives. An analysis is performed and a justification for the relevant suitability (for use in this thesis) of the examined parts is elaborated in chapter 2.

3.3 Network Description

Subway networks are very large and complex infrastructure systems that consist of an extremely high number of different components. This reality can cause many difficulties when attempting to depict the entire network in a single scheme. In order to overcome this burden, components are categorized in major groups making the model easier to handle but simultaneously ensuring that no important elements of subway systems are omitted.

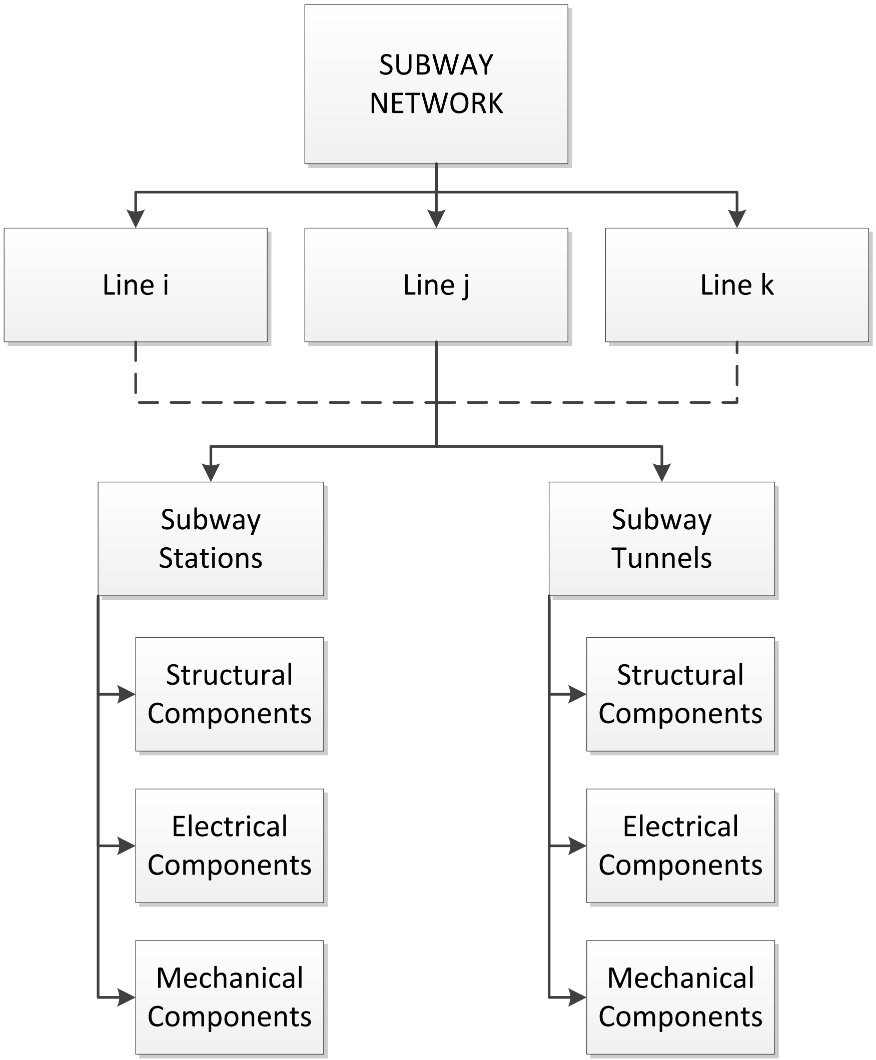


Figure 3.2 Subway Network Diagram

Another concern during the initial stages of this study was the unavailability of information on subway systems. Surmounting this reality, knowledge from general building infrastructure had to be "borrowed", building inspection reports from where components were able to be distinguished and even bidding documents of transit authorities requesting proposals for subway repair works. After careful review of the limited available literature (see section 2.10) and with the proper information filtering, a typical network is defined in Figure 3.2. The network entails 4 separate levels, the network in the higher level that consists of subway lines and then stations and tunnels within each line. Under every station and tunnel there are a number of structural, electrical and mechanical components.

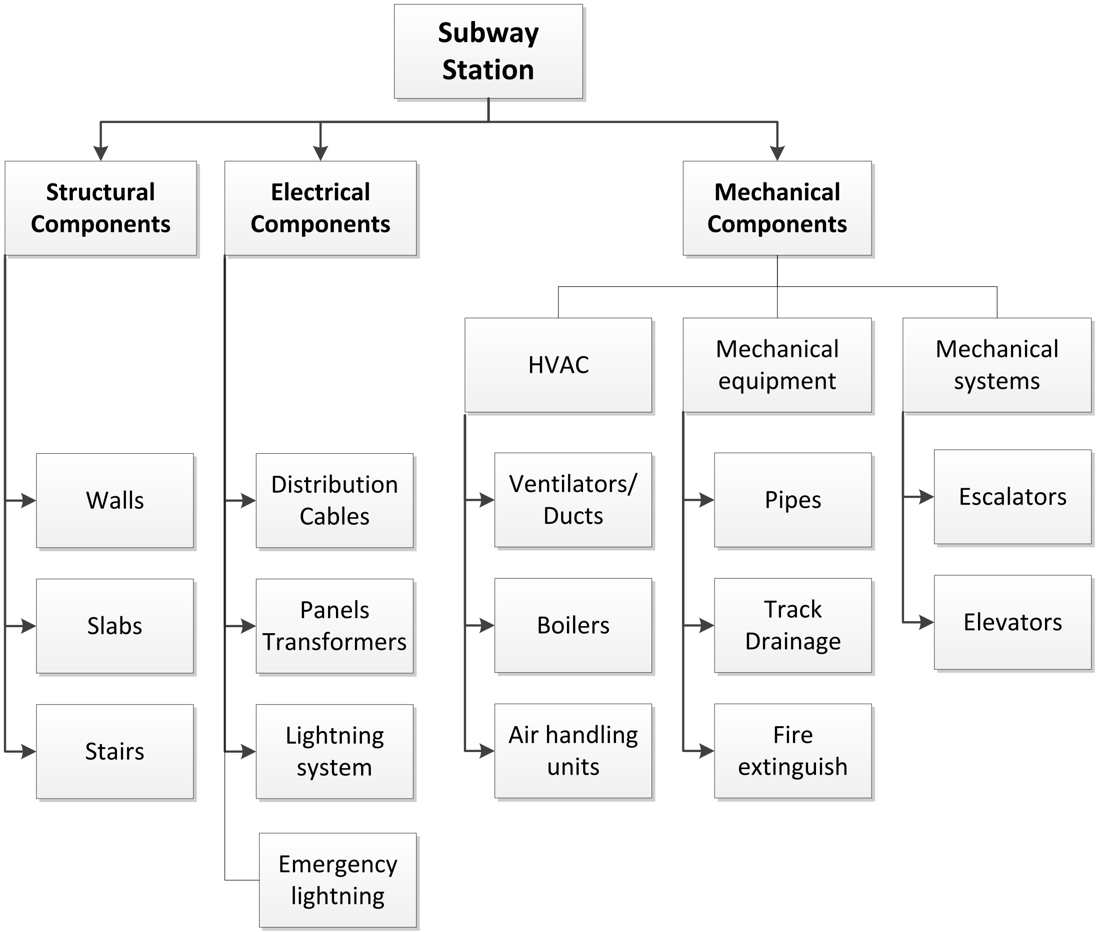


Figure 3.3 Subway Station Components

It should be noted that focus is given in the electrical/mechanical parts of the network. The structural related parts have been studied earlier (Semaan, 2011) and are included in the figures for better understanding. In Figure 3.3 and Figure 3.4, the further subdivision of stations and tunnels in their respecting components can be seen. The difficulty of comparing mechanical components of unequal magnitude and nature prompts the introduction of a supplementary level for the optimum grouping and representation of mechanical infrastructure. Therefore, the three "parent" component groups of HVAC, Mechanical Systems and Mechanical Equipment/Plumbing are inserted to facilitate this anomaly. The remaining components are grouped accordingly under them. For instance, elevators and escalators are evaluated for their contribution to the Mechanical Systems component condition.

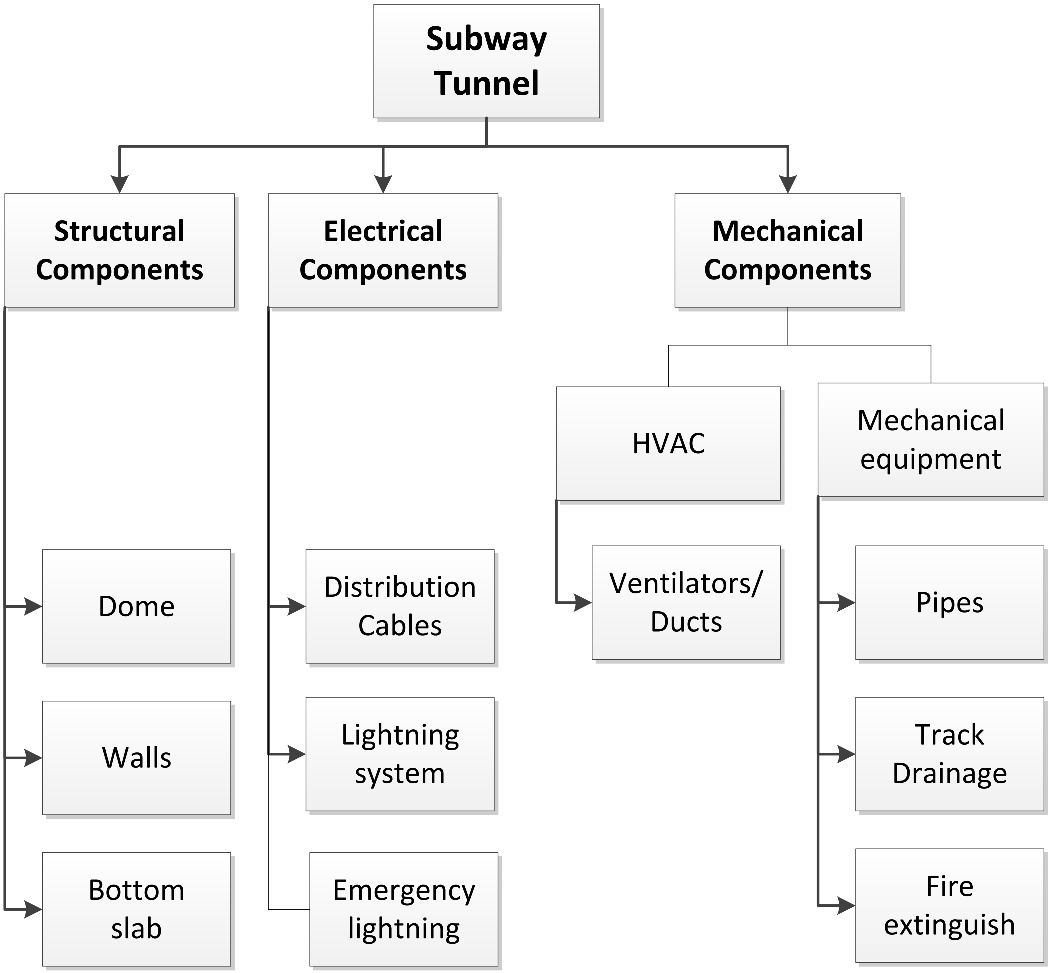


Figure 3.4 Subway Tunnel components

3.4 Condition Assessment Model

The proposed framework is divided into two discrete subdivisions, the condition assessment and the deterioration prediction model. The former one comes chronologically first and is discussed in the following sections. According to the subway networks levels as presented previously, component condition rating commences the process, followed by station/tunnel assessment, subway line and ultimately the entire network's performance evaluation. The detailed flowchart of the condition assessment model is illustrated in Figure 3.5.

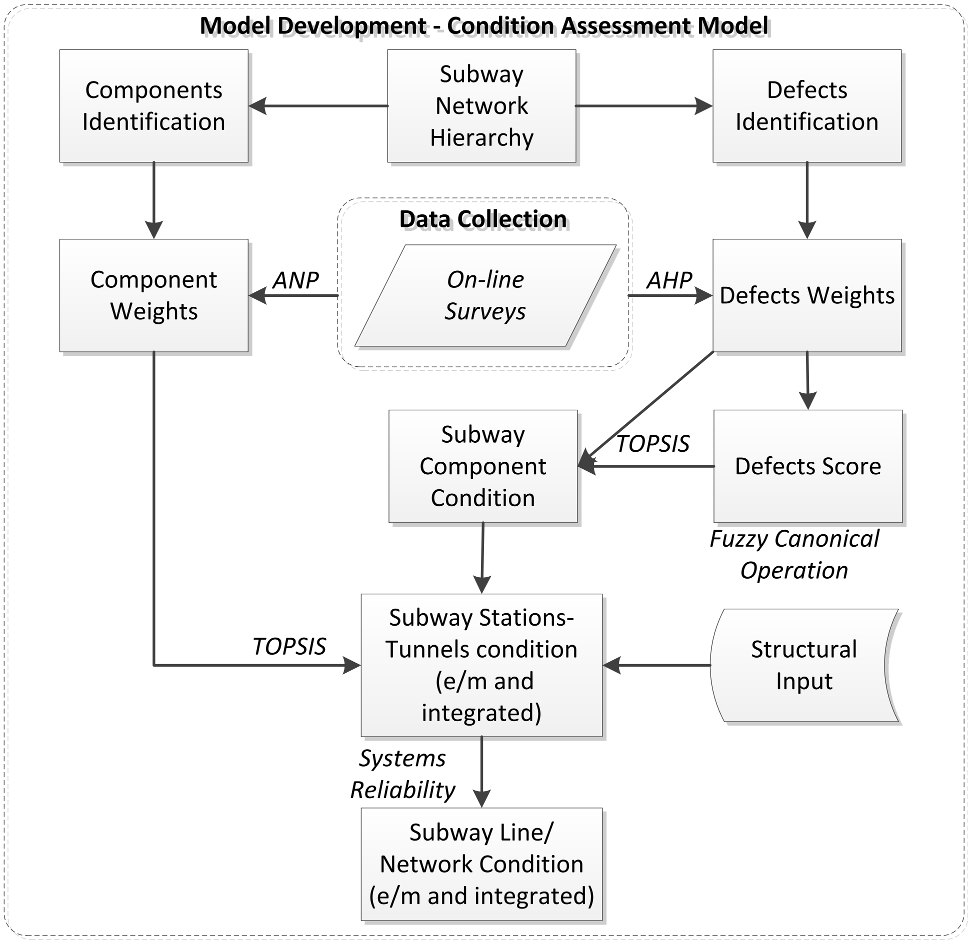


Figure 3.5 Condition Assessment Model Flowchart

3.4.1 Defects Hierarchy

Aiming the upper level of objectivity in the assessment process, it is suggested that the rating is done based on the measurement of actual defects. The first step is to define the main defects that affect the condition of all the components included in the model. Due to the lack of existence of previous models, the main defects of subway electrical and mechanical infrastructure were identified by conducting extensive review of current approaches, inspection reports and lessons learned from building related electrical/ mechanical defects (see section 2.11). The validity of this treatment sources from the fact that it is the building infrastructure (stations and tunnels) of subway systems that is examined. The proposed list of defects along with a brief description is shown in Table 3-1. In Figure 3.6 and Figure 3.7 the hierarchy of defects for each component can be seen.

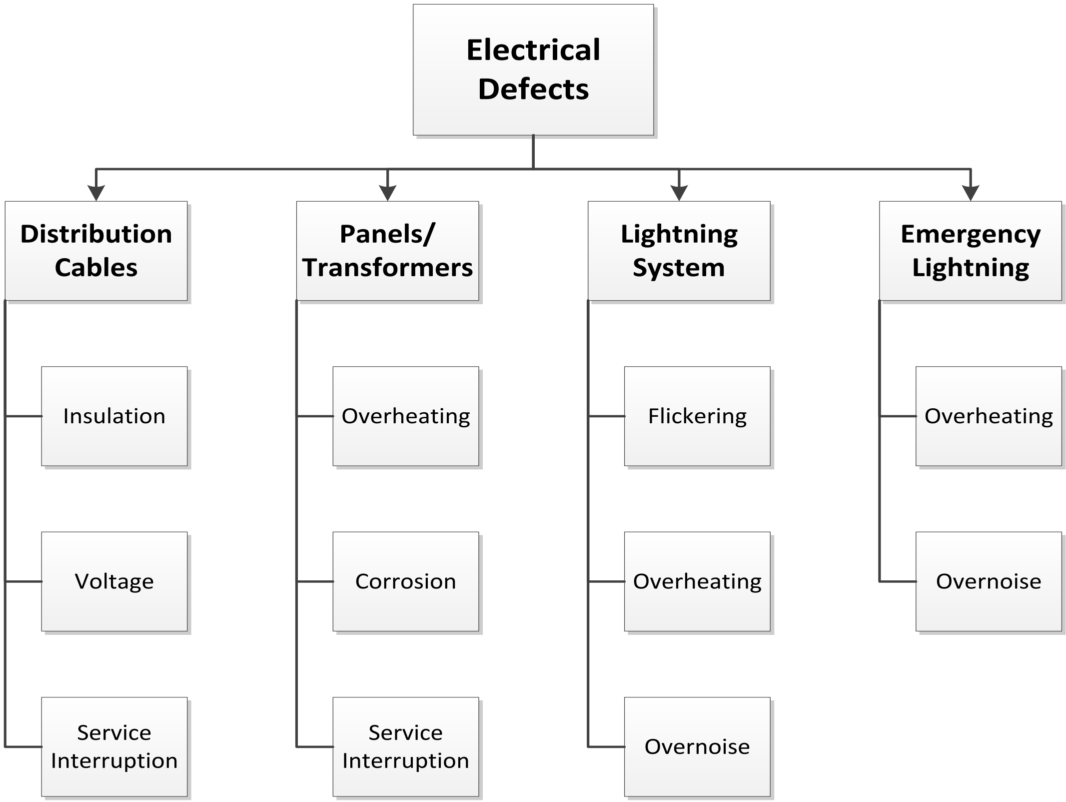


Figure 3.6 Electrical Components' Defects

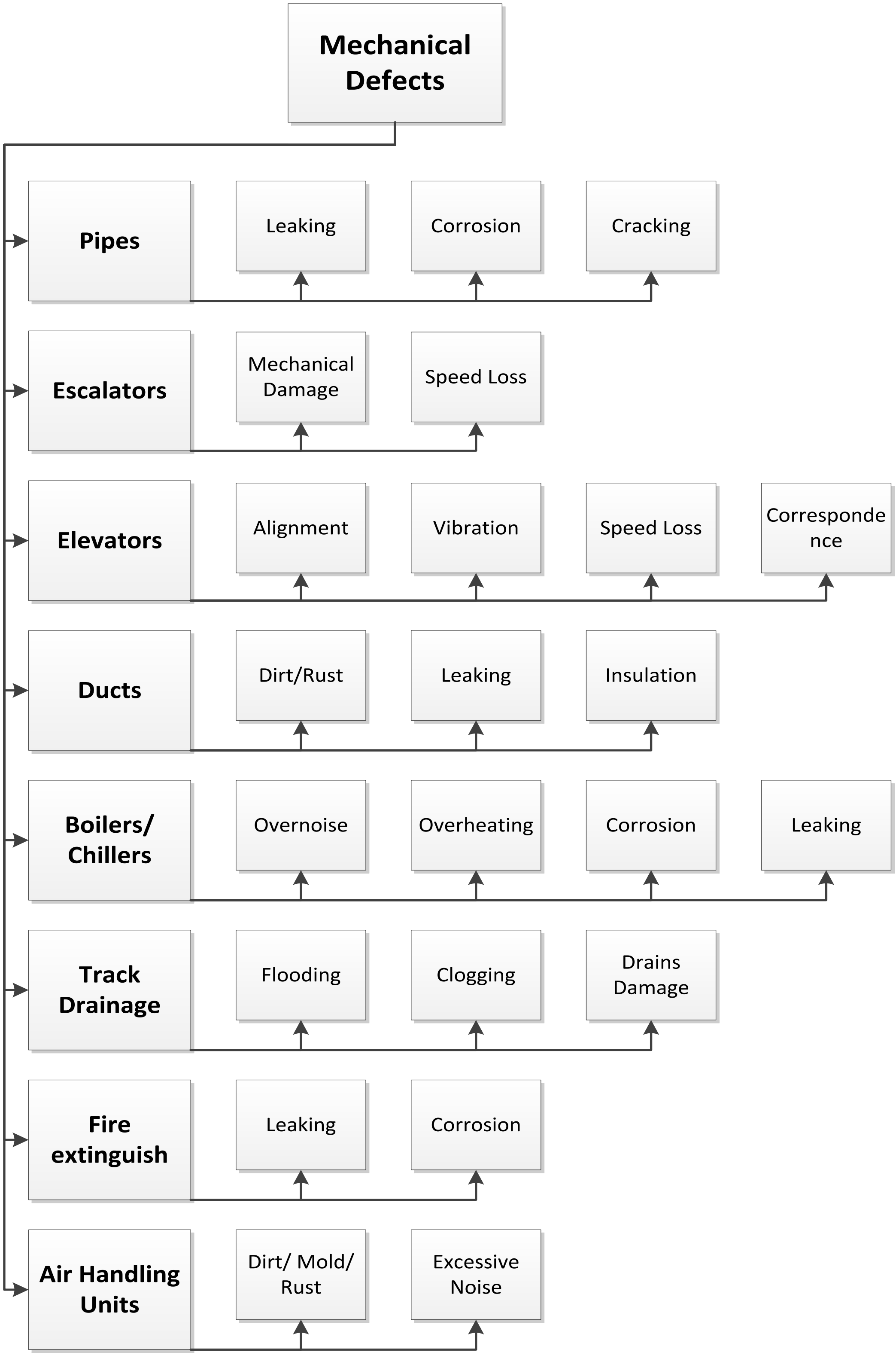


Figure 3.7 Mechanical Components' Defects

Table 3-1 Defects Description

Component	Defect	Description
Distribution Pipes	corrosion	material corrosion due to ageing
	Leaking	water leak from inappropriate joints or material failure
	cracking	cracks of the material allowing excessive leaking
Ventilators/ Ducts	dirt/ rust	accumulation of dust and other particles, rusty surfaces
	Leaking	water leak from inappropriate joints or material failure
	insulation	damaged/insufficient insulation causing leaks or low air quality
Boilers	corrosion	material corrosion due to ageing
	overheating	excessive heat due to false operation
	excessive noise	excessive noise due to false operation
Air Handling Units	Leaking	water leak from inappropriate joints or material failure
	dirt/ mold/ rust	accumulation of dirt and other particles, mold presence, rusty surfaces
	excessive noise	excessive noise due to false operation
Track Drainage	drains damage	damaged drains material
	flooding	insufficient drains service causing water overflow
	clogging	blocked drains
Elevators	alignment	elevation difference with floors
	vibration	excessive undesired turbulence
	speed loss	unstable elevator speed usually slower than designed
	correspondence	late response and large waiting times
Escalators	mechanical damage	material corrosion due to ageing
	speed loss	unstable escalator speed usually slower than designed
Fire Extinguish	corrosion	material corrosion due to ageing
	Leaking	water leak from inappropriate joints or material failure
Distribution Cables	insulation	improper service due to damaged/exposed insulation
	Voltage	voltage drops
	service interruption	failure to service and electric shocks
Panels/ Transformers	corrosion	material corrosion due to ageing
	overheating	excessive heat due to false operation
	service interruption	failure to provide service
Lightning System	flickering	unstable/trembling lightning service
	overheating	excessive heat due to false operation
	excessive noise	excessive noise due to false operation
Emergency Lightning	overheating	excessive heat due to false operation
	excessive noise	excessive noise due to false operation

3.4.2 Defect Weights Calculation

The hierarchical form of the mechanical and electrical defects grants the use of the AHP to determine defect weights. The defects are handled as the decision factors in the pairwise comparison matrices. One matrix is constructed and solved for each component. Data derive from the responses to the questionnaires (see chapter 4) and inserted to the matrix. The consistent-type AHP matrixes are used in this research. This means that a direct comparison between a standard defect and all the remaining is conducted and the remaining can be estimated from the indirect relationship among them. In other words, by knowing the comparison of A versus B and A versus C, the comparison of B and C can easily be extracted. All the AHP-relative computations are done using spreadsheets.

An example of the AHP weight calculation process is provided in Table 3-2. Note that the equations 2.8 – 2.11 as described in literature review are used.

Table 3-2 Defect Weights Calculation with AHP

Lightning	Overheating	Flickering	Excessive noise
Overheating	1	5	5
Flickering	1/5	1	1
Excessive noise	1/5	1	1
Sum	1.400	7.000	7.000

Lightning	Overheating	Flickering	Excessive noise	**Weights**
Overheating	0.714	0.714	0.714	**72%**
Flickering	0.143	0.143	0.143	**14%**
Excessive noise	0.143	0.143	0.143	**14%**

One essential rule that has to be followed is that the summation of defect weights for every component must be equal to unity as it is illustrated in equation 3.1.

$$\sum W_{def,comp} = 1.0 \tag{3.1}$$

Where:

$W_{def,comp}$ = defect weight of the specific component

3.4.3 Defects Evaluation

The state of each component is based on the presence and the extent of the different defects. Currently, most inspection manuals use linguistic terms to describe condition. Following this industry need, the methodology suggests the following defects scale, measured in linguistic terms as seen in Table 3-3 along with the description of each state.

Table 3-3 Defect Linguistic scale

Linguistic Condition	Description
A	**Excellent**
B	**Good, minor defect extent**
C	**Fair, obvious defect presence**
D	**Advanced deterioration**
E	**Very severely deteriorated**

Due to the fact that the end product of the model is a numeric condition index in a zero to ten (0-10) scale, a transformation is required to quantify the qualitative terms in the previous scale. In addition, in an attempt to capture any hint of uncertainties and ensure the smooth distribution and representation of each of the five linguistic scales to a 0-10 scale, every state is represented by a triangular fuzzy number (TFN). In Table 3-4, the proposed fuzzy condition states can be seen.

Table 3-4 Fuzzy representation of defects scale

Linguistic Condition	Description	min value	most probable	max value
A	**Excellent**	**8**	**10**	**10**
B	**Good, minor defect extent**	**6**	**7**	**9**
C	**Fair, obvious defect presence**	**4**	**5**	**7**
D	**Advanced deterioration**	**2**	**3**	**4**
E	**Very severely deteriorated**	**1**	**1**	**2**

In order to complete the transformation, a defuzzification process is needed. The model handles crisp values as inputs and produces a crisp numerical condition index in the end. The graded mean integration representation as it is used in the canonical operation representation of fuzzy numbers is utilized. (Chou, 2003) This technique has been used along with the selected aggregation method in the past (see section 2.9.1). The transformation can be completed by equation.

$$P(Y) = \frac{1}{6}(\mathrm{a} + 4b + c) \tag{3.2}$$

Where:

Y = triangular fuzzy number

P(Y) = crisp value of Y

a = minimum value

b = most probable value

c = maximum value

3.4.4 Aggregation

The next step of the methodology is the aggregation, the combination of weights and scores, to form a single number representing the component condition. The model is utilizing the axioms of TOPSIS as described in the literature review. This technique is selected because it is established under a very sound logic and, under conditions; it can provide a final index.

According to TOPSIS, alternatives are evaluated based on the calculated relative closeness coefficient (c_i). The larger the c_i value is, the better the alternative. A very important drawback that prevents TOPSIS use in its existing form lies to the fact that the technique is dynamic and hence affected by the examined alternatives. In other words, the calculated c_i changes upon the addition or extraction of alternatives. Also, the c_i value depends on the existing ideal and negative ideal solutions as they can be measured from the alternatives.

In order to fit the research scope, a customized version of TOPSIS is suggested, targeting the above described disadvantages and making the technique functional.

Tackling the problem of TOPSIS' dynamic nature, only a single alternative is examined each time, achieving the stability of the calculated c_i. Next, fixed fictitious boundaries are introduced so as to disregard the dependence of the present ideal and negative-ideal solutions. Therefore, each alternative, in this case each component, is examined separately and compared to an ideal alternative that possesses the maximum evaluation value and with a negative-ideal alternative which possesses the minimum evaluation value.

After the above mentioned adjustments, the typical TOPSIS decision problem from equation 2.12 in the literature review now is having the following form:

$$\begin{array}{cc} & \begin{array}{cccc} W_1 & W_2 & \dots & W_m \end{array} \\ D = \begin{array}{c} A_{best} \\ A_i \\ A_{worst} \end{array} & \begin{bmatrix} 10 & 10 & \dots & 10 \\ X_{i1} & X_{i2} & \cdots & X_{im} \\ 10 & 10 & \cdots & 10 \end{bmatrix} \end{array} \qquad (3.3)$$

Where:

W_i = defect weight

X_{ii} = defect evaluation score

A_i = component

A_{best} = ideal component condition

A_{worst} = negative-ideal component condition

As a result of this modification, the c_i is always between the limits of zero (0) and one (1). That was the case in the original TOPSIS as well, but currently there always is an alternative (A_{best}) with relative closeness coefficient equal to one and another alternative (A_{worst}) with coefficient equal to zero. Equations 3.4 – 3.6 describe the previous steps.

$$0 \leq c_i \leq 1 \quad (3.4)$$

$$c_{A,best} = 1 \quad (3.5)$$

$$c_{A,worst} = 0 \quad (3.6)$$

Taking into consideration the alterations explained in this chapter, all the equations illustrated in the literature review regarding TOPSIS can be easily adjusted to incorporate them.

After the customized decision matrix has been established, the next steps, namely the normalized matrix and the weighted normalized matrix can be calculated with the same equations 3.7 and 3.8; the proposed changes do not affect this part.

$$r_{ij} = \frac{\mathrm{Xij}}{\sqrt{\sum_{i=1}^{m} Xij^2}} \quad (3.7)$$

$$V_{ij} = W_j \times r_j \quad (3.8)$$

The ideal and negative-ideal solutions are following with equations 3.9 and 3.10. The V_i^+ is the maximum value among the examined and is always the value of the first row (the A_{best}) and the minimum value is always the value of the last row (the A_{worst}) which is also always equal to zero (0).

$$A^+ = \{(maxV_{ij} | j \in J)\} = [V_1^+, V_2^+, \dots, V_m^+] \quad (3.9)$$

$$A^- = \{(minV_{ij} | j \in J)\} = [V_1^-, V_2^-, \dots, V_m^-] = [0,0,\dots,0] \quad (3.10)$$

Following are the equations 3.11 and 3.12 for ideal and negative-ideal separation measures.

$$S_i^+ = \sqrt{\sum_{j=1}^{n}(V_{ij} - V_j^+)^{\ 2}}\ ,\ i = 1,2,\dots,m \tag{3.11}$$

$$S_i^- = \sqrt{\sum_{j=1}^{n}(V_{ij})^{\ 2}}\ ,\ i = 1,2,\dots,m \tag{3.12}$$

The final step of TOPSIS is the calculation of the relative closeness coefficient (C_i) which can be seen in equation 3.13. This is the measurement based on which the ranking of the alternatives is done. In this research, the c_i is the basis for the final component condition index.

$$C_{i=}\frac{S_i^-}{(S_i^+ + S_i^-)}\ ,\ 0 < C_i < 1,\ i = 1,2,\dots,m \tag{3.13}$$

3.4.5 Component Condition

Since the end product, the component condition index should be in a 0-10 scale, a simple multiplicative transformation is the last step of the calculation process as shown in equation 3.14.

$$CI_{comp} = 10 \times C_i \tag{3.14}$$

Where:

c_i = relative closeness coefficient

A_{best} = ideal alternative

A_{worst} = negative-ideal alternative

CI_{comp} = component condition index

The entire customized TOPSIS process is done with the use of spreadsheets.

3.4.6 Component Weights

After completing the previous steps and calculating the component condition index, the shift upwards in the subway network becomes the objective. The following level is the subway station and tunnel. The previously examined components contribute in a different extent to the performance and condition of a station or a tunnel. Hence, the estimation of component relative importance weights is required. In contrast with the case of defects, the ANP is utilized in this stage.

As stated in the literature review, the advantage of ANP to capture interaction among factors in the same level of the network is applied in the case of subways. The suggested subway network scheme discussed before is dividing infrastructure in structural, electrical and mechanical infrastructure. It is essential to comprehend that the state of each infrastructure category affects the remaining. For instance, although escalators belong to the mechanical category and distribution panels to the electrical, still a failure of distribution panels to provide service will cause the pause of the operation of escalators. Attempting to address this reality, an inner dependence loop is attached in this level (Figure 3.8), allowing the execution of three additional comparisons, namely structural versus mechanical, structural versus electrical and electrical versus mechanical (see Appendix).

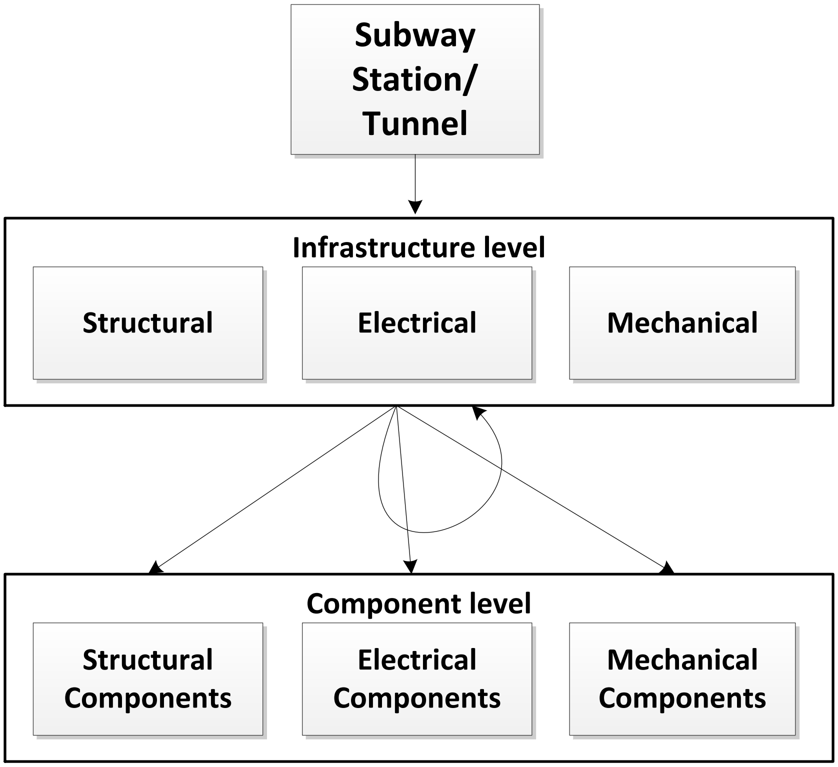


Figure 3.8 Infrastructure level interdependence

Again, the rule of weights' summation should be equal to one is followed for the case of different infrastructures and for the total weights of stations and tunnels. The following equations 3.15 – 3.16, provide the template for these calculations.

$$\sum W_{infr,s/t} = 1.0 \tag{3.15}$$

$$\sum Wcomp_{MechGroup}^{s/t} = W_{MechGroup}^{s/t} \tag{3.16}$$

Where:

W = weight

Comp = component

Infr = electrical or mechanical infrastructure

s/t = station or tunnel

MechGroup = HVAC or Mechanical Equipment or Mechanical Systems (extra hierarchy level of mechanical infrastructure)

The final weights to be used for the calculation of the integrated structural, electrical and mechanical condition of stations and tunnels are the relevant decomposed component weights. The decomposed weight is generated form the multiplication of the "local" component weight with the "parent" weight e.g. the product of "Pipes" weight with "mechanical infrastructure" weight.

$$\sum W_{infr,s/t}{}' = 1.0 \tag{3.17}$$

$$W_{comp,s/t}{}' = W_{infr,s/t} \times W_{comp,s/t} \tag{3.18}$$

Where:

W′ = global weight

W = local weight

Comp = component

Infr = structural or electrical or mechanical infrastructure

s/t = station or tunnel

With the implementation of equations 3.15 - 3.18, the global weights to be included in the final model for assessing the integrated condition of subway stations and tunnels can be acquired. The ANP weights are obtained using the "Super Decisions" software.

3.4.7 Station and Tunnel Condition

As soon as component weights are calculated, the subsequent process is the combination of component weights and scores in order to compute the condition index of stations and tunnels. The previously calculated component condition index (CI_{comp}) plays the role of the component score. The customized TOPSIS technique is utilized for the purpose of aggregation. In equation 3.19 the adjusted TOPSIS decision problem D can be seen, implemented for the case of station condition.

$$D = \begin{array}{c} \\ A_{best} \\ A_i \\ A_{worst} \end{array} \begin{array}{c} \begin{array}{cccc} W_1 & W_2 & \dots & W_m \end{array} \\ \begin{bmatrix} 10 & 10 & \dots & 10 \\ X_{i1} & X_{i2} & \cdots & X_{im} \\ 10 & 10 & \cdots & 10 \end{bmatrix} \end{array} \tag{3.19}$$

Where:

W_i = component weight

X_{ii} = component condition index

A_i = station

A_{best} = ideal station

A_{worst} = negative-ideal station

With this decision matrix/equation as the initiation point, the TOPSIS process (equations 3.4 – 3.13) is implemented step by step and the final equation (3.20) is used for the condition index estimation.

$$CI_{infr,bldg} = 10 \times C_i \tag{3.20}$$

Where:

c_i = relative closeness coefficient

infr = electrical or mechanical infrastructure

bldg = station or tunnel

At this point, a very important note has to be done. By selecting the desirable component weights from equations 3.15 – 3.18, the results can be representative of the electrical condition of stations or tunnels ($CI_{el,stat}$ and $CI_{el,tun}$) or the mechanical condition of them ($CI_{mech,stat}$ and $CI_{mech,tun}$).

A great addition of this research springs from the ability of the developed methodology to integrate electrical and mechanical results with the existing state-of-the-art research on structural condition of subway systems. More specifically, as presented in the literature review, the SUPER model (Semaan, 2011) provides a structural condition index for stations and tunnels. As this need for integration has been foreseen in the beginning of this study, questions for structural importance have been included in the questionnaire. That gives the chance of calculating a structural weight with ANP. By having the structural weight and the structural score, the customized TOPSIS can be easily implemented as seen in equation 3.21 for the computation of the integrated structural, electrical and mechanical condition of subway stations and tunnels which is called STREM (STRuctural/Electrical/Mechanical).

$$D = \begin{array}{c|cccc|} & W_1 & W_2 & \dots & W_m \\ \hline A_{best} & 10 & 10 & \dots & 10 \\ A_i & X_{i1} & X_{i2} & \cdots & X_{im} \\ A_{worst} & 10 & 10 & \cdots & 10 \\ \hline \end{array} \tag{3.21}$$

Where:

W_i = infrastructure weight

X_{ii} = station or tunnel condition index

A_i = station or tunnel

A_{best} = ideal station or tunnel

A_{worst} = negative-ideal station or tunnel

After following the entire process (equations 3.4 – 3.13), with equation 3.22 the STREM is calculated.

$$STREM_{bldg} = 10 \times C_i \tag{3.22}$$

Where:

c_i = relative closeness coefficient

bldg = station or tunnel

It has to be mentioned here that a performance threshold has to be entered from the users for each of the three infrastructure types. A general performance limit of 4 out of 10 is adapted in this research. Taking this into account, the model should not be utilized in the event of any decision attributes (infrastructure type or component) records a condition of less than 4. The process should immediately be stopped at this point and urgent repair activities should be ordered. After renovation, the model can be implemented safely without the risk of masking extensive deterioration issues or significant failures.

3.4.8 Line Condition

The following level of the subway network is the subway line level. A line consists of a number of stations and tunnels. Consequently, the current condition of the line should be dependent on the condition of its stations and tunnels. The computational process can be established in the following:

- Identify the number of stations and tunnels in the line
- Propose a reliability-based structure
- Calculate the subway line condition.

In this case, a reliability approach for the solution of lines is chosen as it has also been used in the past (Semaan, 2011) in subway networks and in other infrastructures (Salman, 2011, Ghodoosi, 2013). The theory of reliability with systems connected in parallel or in series can sufficiently be implemented for the integration of stations and tunnels performance. Subway stations are handled as redundant systems. The explanation of this statement comes from the reality that if one station is not functioning, that does not automatically mean the failure of the entire line to operate. Passengers can be served in the adjacent stations or use alternatives routes. Theoretically, all stations should stop operating to cause the entire line to completely shut down.

Following the same pattern as in the case of stations, subway tunnels are redundant systems as well, since failure of one tunnel does not necessarily yield the complete failure of the line. Passengers can still be served alternatively. The case of tunnels has a higher degree of complexity than stations. For instance, a complete structural collapse of a tunnel will definitely not allow any trains passing through it. Even in this case, subway lines can still function by performing track switches in the previous tunnels and reversing the moving direction. If that possibility does not exist, a single platform can be utilized for both directions. It should be noted that neighboring stations and tunnels do not affect the functionality of each other. At last, the sub-part of stations is connected in series with the sub-part of tunnels. That is because as explained, failure of either of these two sub-parts will cause the shutdown of the entire system. Schematically, this can be seen in the diagram of Figure 3.9.

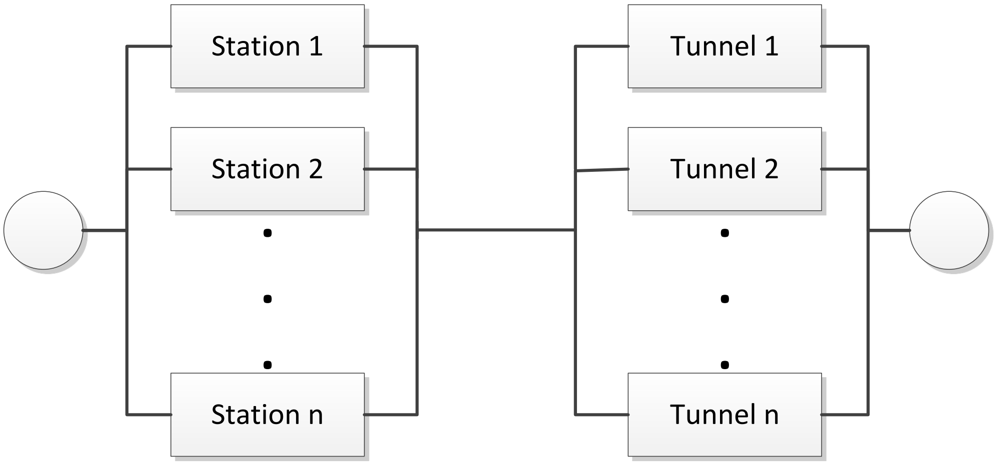


Figure 3.9 Subway Line Reliability Diagram

The mathematical formula representing the above diagram and allowing the calculation of the subway line condition can be seen in equation 3.20.

$$STREM_{lin} = \left[1 - \prod_{i=1}^{n}(1 - STREM_{sta,i})\right] \times \left[1 - \prod_{j=1}^{m}(1 - STREM_{tun,j})\right] \qquad (3.20)$$

Where:

n, m = number of stations and tunnels in line

$STREM_{sta,i}$ = Integrated condition of station i

$STREM_{tun,j}$ = Integrated condition of tunnel j

3.4.9 Network Condition

Finally, with the performance of lines been identified, the whole network performance estimation becomes feasible. In a similar manner, the entire subway network consists of different lines that impact its condition. The next steps are followed:

- Identify the number of lines
- Propose a reliability-based diagram
- Calculate subway network condition

Subway lines are considered to be redundant systems as failure of a single line does not enforce the failure of the entire system. In the occasion of complete failure of all the lines, then the entire network collapses. In Figure 3.10, the related diagram can be seen.

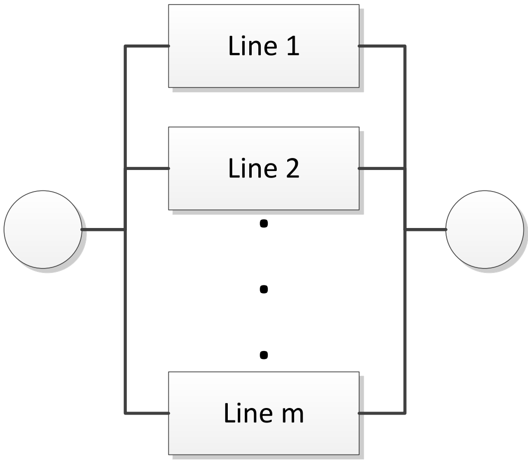


Figure 3.10 Subway Network Reliability Diagram

Following, is the equation 3.21, utilized to compute the subway network performance.

$$STREM_{netw} = \left[1 - \prod_{k=1}^{l}(1 - STREM_{lin,k})\right] \tag{3.21}$$

Where:

l = number of lines in network

$STREM_{lin,k}$ = Integrated condition of line k

3.5 Condition Prediction Model

A very important addition to any condition assessment model is a module for future performance forecasting. An estimation of the deterioration profile of subways and all of its levels (e.g. components, stations, tunnels, lines), provides managers a powerful tool in the decision making process for budget allocation purposes and rehabilitation planning. By having the knowledge of the future state of the system or at least an estimation about it, managers can determine how to prioritize infrastructure for repair works and whether to assign a larger or less amount of capital to specific items. The detailed flowchart of the condition prediction model is demonstrated in Figure 3.11.

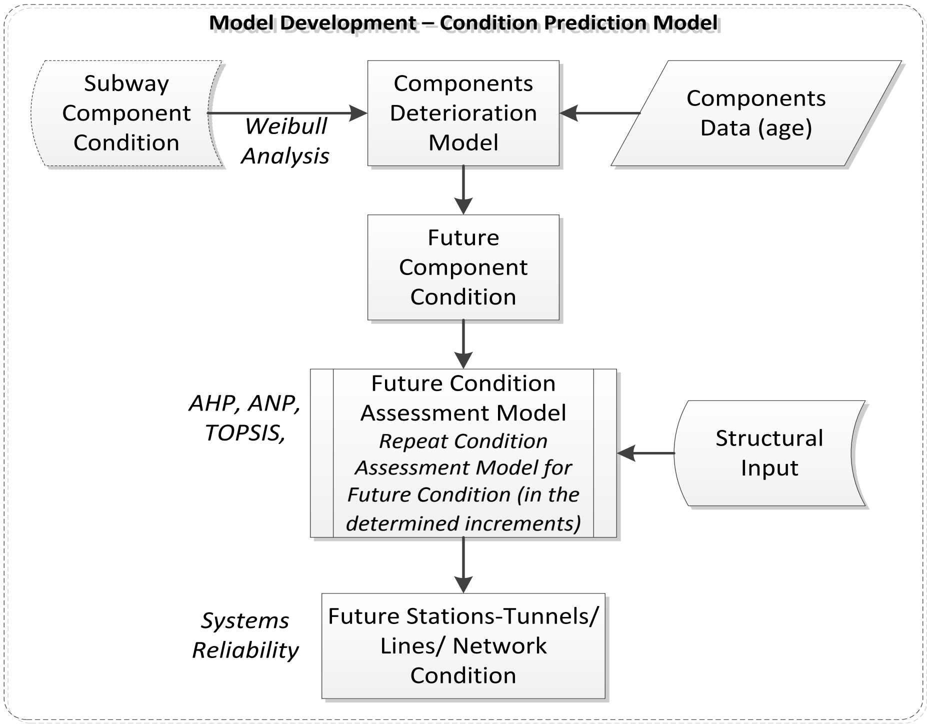


Figure 3.11 Condition Prediction Model Flowchart

3.5.1 Component Deterioration Model

In this research, Weibull Analysis is used for the scope of deterioration modelling, more specifically, the Weibull Reliability function. This approach has been used in the past for various building components (Grussing et al. 2006) and structural performance of subways (Semaan, 2011). It can also be adapted in this study. The graph of the Weibull reliability function starts from 100% performance and an almost steady state for some time. Then decreases quite rapidly and towards the end this decrease becomes more slow. A similar pattern can be identified for the examined building components. In the early stages of their life, they perform to the maximum until the begin deteriorating, slightly at first, faster later and before approaching the components' service life, the deterioration develops with a much reduced speed until the complete failure.

One of the main advantages of the Weibull approach is the fact that in order to be solved only two (2) pieces of information are required, namely the age and the current condition of the component. That element really solves the hands of engineers, managers and researchers, since inspection reports of subway systems are very scarce and most of the times are more localized to address specific issues during a certain period. Other commonly used methods, such as the Markovian models, demand the input of a significantly larger amount of data, thus making their development more time-consuming and in many cases not even applicable or based on many assumptions.

From the literature review, equation 3.22 is the Weibull reliability function which can be transformed for the purposes of this study into equation 3.23.

$$R(t) = e^{-\left(\frac{t-\alpha}{\tau}\right)^{\delta}} \tag{3.22}$$

Where:

α = location parameter

τ = scale parameter

δ = shape/slope parameter

t = time

$$CI_{comp}(t) = a \times e^{-\left(\frac{t}{\tau}\right)^{\delta}} \tag{3.23}$$

Where:

$CI_{comp}(t)$ = Component Condition Index

t = time

α = initial condition

τ = scale parameter

δ = deterioration/slope parameter

To solve equation 3.23:

CI_{comp} = known from the condition assessment model

t = known, difference between inspection and construction years

α = 1

δ = 3, provides the smoothest inclination (δ should be >1 and an odd number)

The parameter τ is the only unknown, so it is easy to be calculated. After finding τ, the deterioration curve can be designed in the user's desirable time intervals. In Figure 3.12, a typical component deterioration profile is shown.

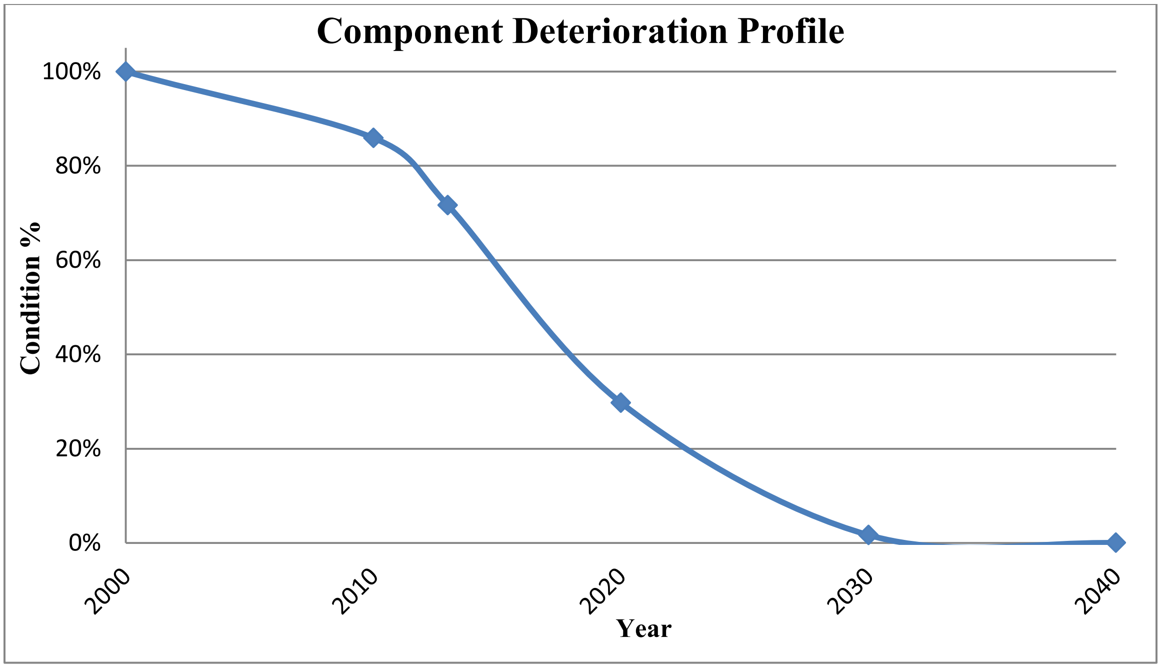


Figure 3.12 Typical Deterioration Curve

3.5.2 Station/ Tunnel/ Line/ Network Deterioration Model

Upon constructing deterioration curves for components, the challenge is the modelling of the deterioration of the entire stations and tunnels. Taking a look at the condition assessment model for stations and tunnels, their performance depends on the one from their components. Since the future state of every component is a given, the complete process as described in sections 3.4.7 - 3.4.9 can be repeated for the future years.

For example, after implementing Weibull theory, the deterioration curves of the components are known. From these curves, the future condition of the component can be easily found for a specific time. Having these future conditions as known variables, the ANP/TOPSIS related steps are implemented and the STREM (STRuctural/Electrical/ Mechanical) indexes for station and tunnels are calculated. Subsequently, by applying the reliability related steps, the STREM for subway lines and the entire network is computed. The specific flowchart summarizing the entire process is seen in Figure 3.13.

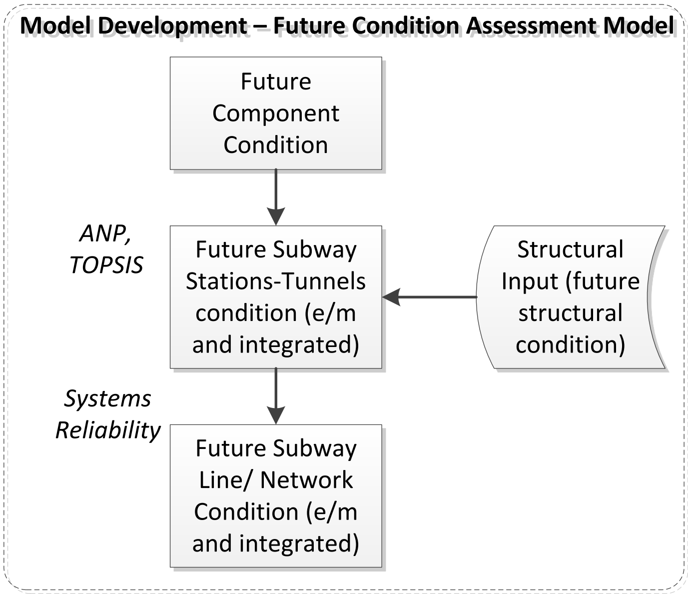


Figure 3.13 Condition Prediction Model-Future Condition Assessment

It has to be noted, that the deterioration profile of the remaining levels of the network other than the components do not obey any Weibull rules and are not the product of drawing a specific equation. They are a line connecting all the future calculated condition indexes.

3.6 STREM Automated Tool

The entire condition assessment and performance prediction methodology analyzed and explained in details in this chapter has been fully embedded in a computer application. It is called "STREM Automated Tool" due to its structural, electrical and mechanical features. It is a completely user-friendly platform that does not require the advanced knowledge of the background methodology for the users to be able to use it. The basic program used for the construction of the software is the Matlab® mathematical tool along with Microsoft Excel sheets.

Consecutive windows pop up, requiring the input of the user in order to proceed and calculate the examined case. That required information is:

- Network size (number of lines, stations and tunnels)
- Component defects evaluation
- Component age
- Inspection Year

The STREM Automated Tool is presented in details in Chapter 6.

3.7 Summary

A new methodology for subway condition assessment and performance prediction called STREM Model has been developed. A complete subway network hierarchy is proposed, covering structural, electrical and mechanical aspects of the infrastructure. The STREM Model is assessing the condition of the entire subway networks, level by level, from the components to the stations and tunnels, from there to the lines and eventually to the network level. The condition rating is based on the presence of actual defects, thus breaking down the process to each component's defects and discarding a significant source of uncertainty. Multi-criteria Decision Analysis techniques are implemented throughout the methodology as they are or after customization. The AHP and TOPSIS are utilized for the calculation of the component condition index (CI_{comp}). The calculation of station and tunnel condition index, with the use of ANP and TOPSIS follows and the results can be focusing on either infrastructure type or be integrated ($CI_{el,stat}$ and $CI_{mech,stat}$, $CI_{el,tun}$ and $CI_{mech,tun}$, $STREM_{sta}$ and $STREM_{tun}$). Upon completion of this level's computations, the STREM model allows for the calculation of the performance of subway lines and finally the entire network ($STREM_{lin}$ and $STREM_{netw}$). Additionally, subway performance deterioration curves are constructed based on the deterioration profiles of the components. The component deterioration profile is easily designable since it requires only two inputs, namely component age and current condition. Finally, the entire process is incorporated in a user-friendly platform called "STREM Automated Tool" facilitating the use of the complex developed methodology by transit authority personnel, managers, engineers and researchers without having to go through any mathematical calculation process.

4 Data Collection

4.1 Introduction

The methodolody requires some data to be finalized and ready for implementation in actual subway network cases. Two information groups are needed:

a) Defect weights data

b) Component weights data

In both cases, the necessary information is collected through questionnaires. An on-line survey was created incorporating questions for both defects and components feedback. Additionally, a website was created to host the designed survey and will be presented in details later. An analysis is performed that categorizes the respondents in relevant groups.

4.2 On-line survey

4.2.1 Metro Network Performance Website

Due to limitations in the graphic design of the application used to construct the on-line survey, a "parent" website was created to accommodate all the necessary information of the project. This platform was developed with the "Google sites" engine. In Figure 4.1, a partial snapshot of the opening page is shown, where the title of the project and all the information about the research and its objectives is released to the users.

Home

Department of Building, Civil and Environmental Engineering

Subway Systems Condition Assessment and Deterioration Prediction

This survey is part of a research conducted at Concordia University, Construction and Engineering Management graduate program in Montreal, under the title: *"Subway Systems Condition Assessment and Deterioration Prediction"*. The purpose of this survey is to analyse the effect of different electrical and mechanical components and defects of subway systems on the performance of subway stations, tunnels and rate their relative importance to each other. The long-term scope of the research is the development of an integrated automated tool for condition assessment and prediction of subway networks.

The questionnaire in the link posted, includes 3 parts, a) importance of subway infrastructure components, b) electrical and mechanical defects and c) subway systems operations. You can complete any part that reflects to your specialty. Auxiliary figures and guidelines are provided below.

Approximate completion time is less than 10 minutes. Remember that in this survey opinions are collected, so there are no right or wrong answers. Any personal information will be absolutely confidential.

ONLINE SURVEY *

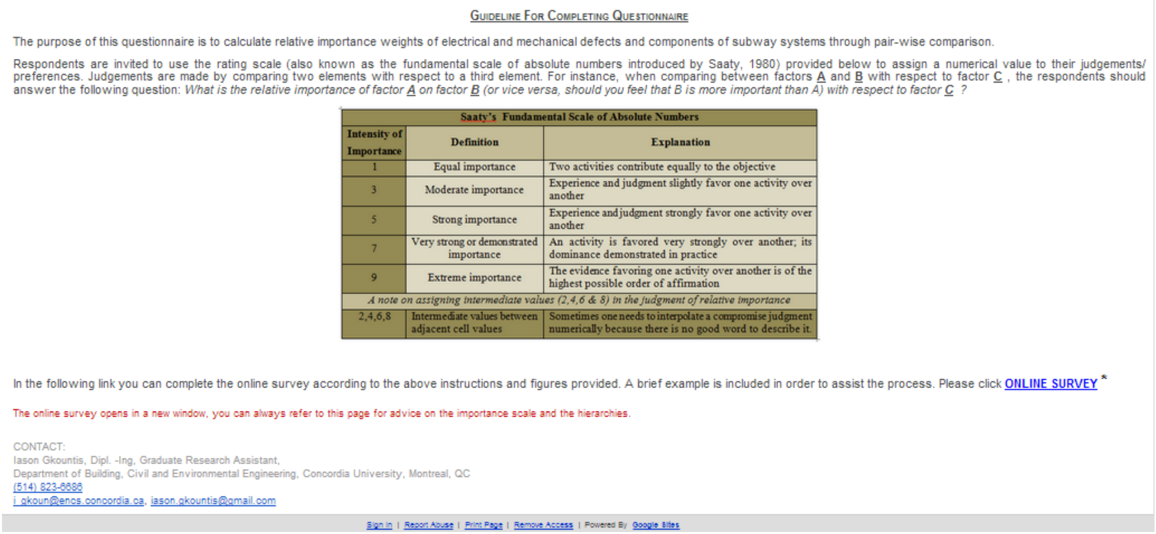
*The online survey opens in a new window, you can always refer to this page for instructions and assistance to the survey completion.

The hierarchies of subway system components and their major defects are shown in the next figures.

Figure 4.1 Metro Network Performance Website Home Screen

Scrolling down the page, more details about the concept of the study are introduced including the proposed diagram of subway networks with the break-down of all its components. The hierarchies of the examined mechanical and electrical defects are also presented. The relevant figures from sections 3.3 – 3.4 are provided to the users for better understanding.

The website concludes with the essential guidelines about the completion of the survey which can be reached through the provided hyper-link (Figure 4.2). Guidelines include a quick description of the nature of the questions as well as the Saaty's Fundamental Scale, the comprehension of which is vital for the proper answers-entries in the survey.



GUIDELINE FOR COMPLETING QUESTIONNAIRE

The purpose of this questionnaire is to calculate relative importance weights of electrical and mechanical defects and components of subway systems through pair-wise comparison.

Respondents are invited to use the rating scale (also known as the fundamental scale of absolute numbers introduced by Saaty, 1980) provided below to assign a numerical value to their judgements/ preferences. Judgements are made by comparing two elements with respect to a third element. For instance, when comparing between factors A and B with respect to factor C , the respondents should answer the following question: *What is the relative importance of factor A on factor B (or vice versa, should you feel that B is more important than A) with respect to factor C ?*

Saaty's Fundamental Scale of Absolute Numbers

Intensity of Importance	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 or demonstrated 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
A note on assigning intermediate values (2,4,6 & 8) in the judgment of relative importance		
2,4,6,8	Intermediate values between adjacent cell values	Sometimes one needs to interpolate a compromise judgment numerically because there is no good word to describe it.

In the following link you can complete the online survey according to the above instructions and figures provided. A brief example is included in order to assist the process. Please click ONLINE SURVEY *

The online survey opens in a new window, you can always refer to this page for advice on the importance scale and the hierarchies.

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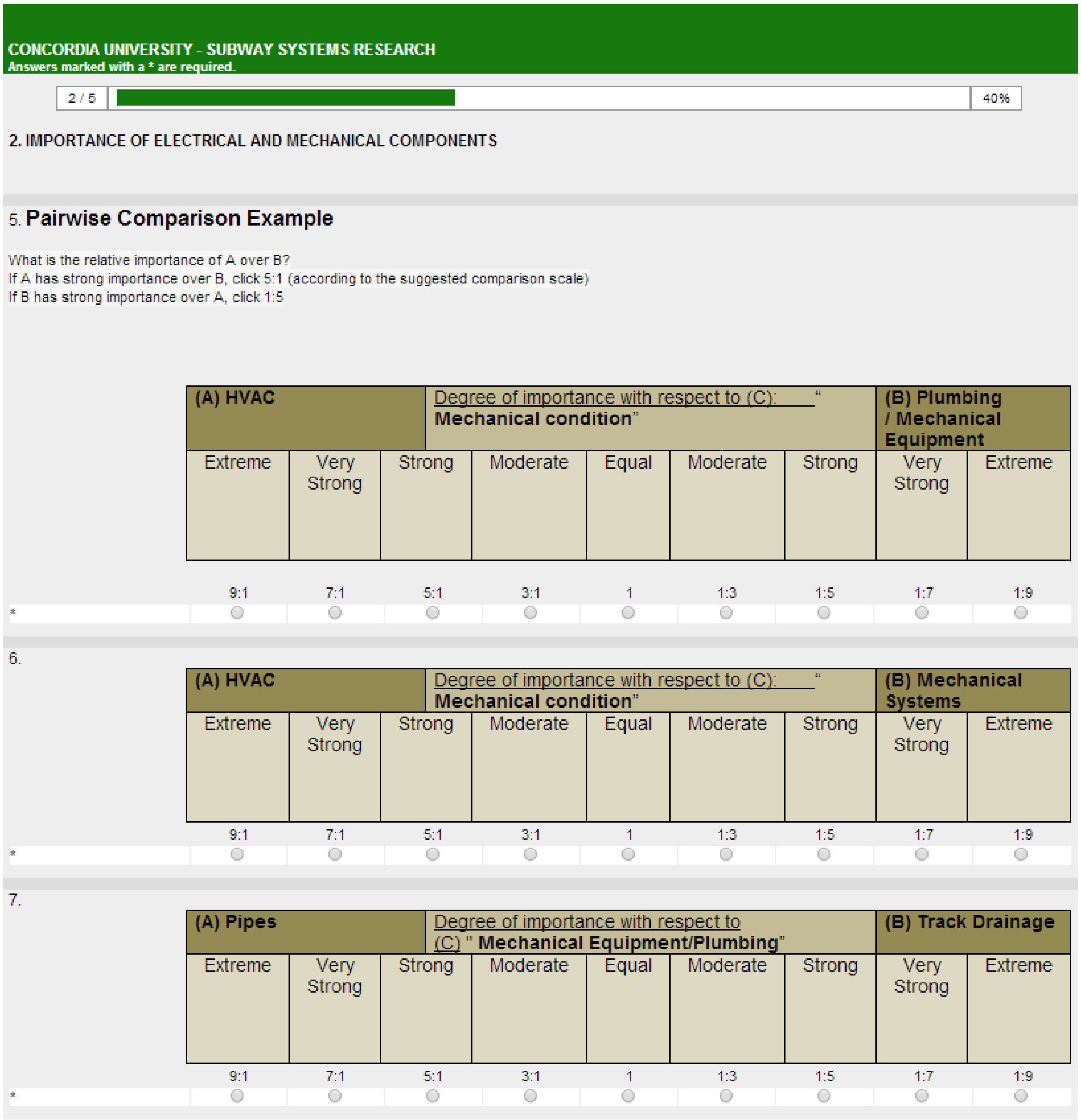
Figure 4.2 Metro Network Performance Website Guidelines

4.2.2 The on-line Survey

The questionnaire itself, which can be reached through the hyperlink provided in the Metro Network Performance website, is designed with the use of the "Survey Expressions" platform. In the survey itself, all the questions about the importance of components, defects and infrastructure (structural, electrical and mechanical) are included. A pairwise comparison table is provided for each case and the users have the possibility to click on the preferred importance scale that best describes their judgment towards the relative importance of the investigated elements. Briefly, the type of questions asked, follow the form of:

“What is the relative importance of A over B with respect to C?”

An example is provided to the users as well for better understanding. In Figure 4.3, a snapshot of the on-line survey is illustrated.



CONCORDIA UNIVERSITY - SUBWAY SYSTEMS RESEARCH
Answers marked with a * are required.

2 / 5 40%

2. IMPORTANCE OF ELECTRICAL AND MECHANICAL COMPONENTS

5. **Pairwise Comparison Example**

What is the relative importance of A over B?
If A has strong importance over B, click 5:1 (according to the suggested comparison scale)
If B has strong importance over A, click 1:5

	(A) HVAC		Degree of importance with respect to (C): “ **Mechanical condition**”					**(B) Plumbing / Mechanical Equipment**	
	Extreme	Very Strong	Strong	Moderate	Equal	Moderate	Strong	Very Strong	Extreme
	9:1	7:1	5:1	3:1	1	1:3	1:5	1:7	1:9
*	○	○	○	○	○	○	○	○	○

6.

	(A) HVAC		Degree of importance with respect to (C): “ **Mechanical condition**”					**(B) Mechanical Systems**	
	Extreme	Very Strong	Strong	Moderate	Equal	Moderate	Strong	Very Strong	Extreme
	9:1	7:1	5:1	3:1	1	1:3	1:5	1:7	1:9
*	○	○	○	○	○	○	○	○	○

7.

	(A) Pipes		Degree of importance with respect to (C) " **Mechanical Equipment/Plumbing**”					**(B) Track Drainage**	
	Extreme	Very Strong	Strong	Moderate	Equal	Moderate	Strong	Very Strong	Extreme
	9:1	7:1	5:1	3:1	1	1:3	1:5	1:7	1:9
*	○	○	○	○	○	○	○	○	○

Figure 4.3 On-line Survey

The complete survey is included in the Appendix. The information from respondents is stored and saved in an online sheet provided by the survey software and are extracted manually and booted in spreadsheets for the calculation process.

4.3 Responses

Two target groups were identified suitable to complete the survey as follows:

- Transit Authorities
- Building Engineers

The survey was mainly targeting North-American transit authorities but also was sent to Metro systems globally. Among others, feedback from Societe de Transport de Montreal (STM), Toronto Transit Commission (TTC), Chicago Transit Authority (CTA), London Underground Limited, Singapore Mass Transit Rapid Trains Limited, Los Angeles County Metropolitan Transportation Authority, Doha Metro and consultant firms from New York, Chicago and Europe was obtained. A total of seventy (70) people were contacted and twenty-three (23) full responses were collected and taken into account in the model development. Six (6) more questionnaires that were incomplete were disregarded. That forms a 32% response rate.

The respondents can be classified in two ways, based on their infrastructure experience and their position level. In Figure 4.4 and Figure 4.5, the analytic information of respondents and relative pie-charts can be seen.

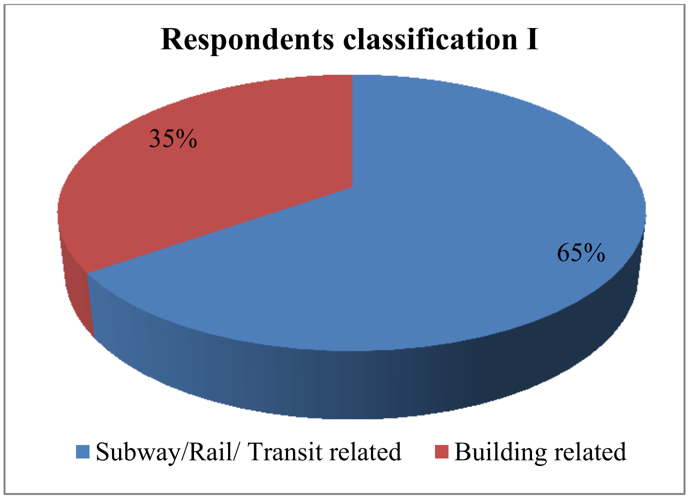


Figure 4.4 Respondents Classification I

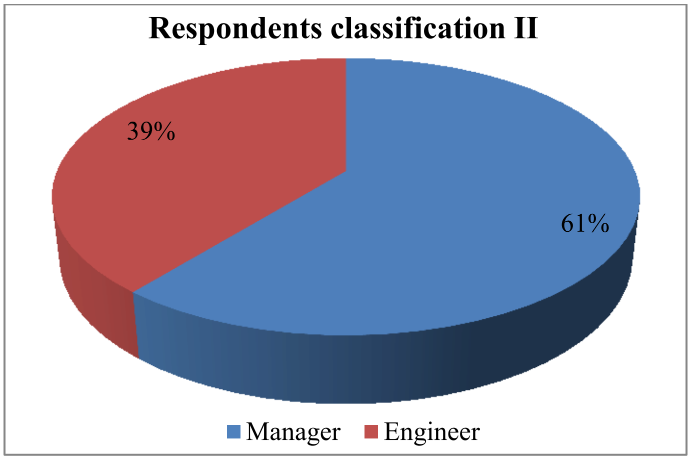


Figure 4.5 Respondents Classification II

4.4 Analysis

An initial analysis is conducted to study the response patterns. The gathered inputs from the online surveys are checked. In Table 4-1, an analytical description of a sample of questions is shown. For every question, the number of times each response is inserted is counted and also a categorization of the responses based on their values (e.g larger than

1, smaller than 1). This table extends to questions 5 – 12 from the on-line survey (the entire survey can be found in the appendix) and a brief description of each question is also provided.

Table 4-1 Sample of Input Data Analysis

Description	HVAC/ Mech Equipment	HVAC/ Mech Systems	Pipes/ Drains	Pipes/ Fire Ext	Elevators/ Escalators	Boilers/ Ducts	Boilers/ Air Handling	Cables/ Panels
Question # Response	5	6	7	8	9	10	11	12
1	8	5	9	5	5	7	11	12
3	2	1	2	1	3	2	1	1
5	1	1	1	1	3	4	3	3
7	1	0	1	0	0	4	3	0
9	0	0	0	0	0	0	0	0
1/3	2	5	3	6	0	5	3	4
1/5	6	4	3	6	9	1	1	3
1/7	3	6	4	1	3	0	1	0
1/9	0	1	0	3	0	0	0	0
sum	23	23	23	23	23	23	23	23
AVG	1.23	0.71	1.27	0.73	1.36	2.73	2.23	1.39
Count >1	4	2	4	2	6	10	7	4
Count <1	11	16	10	16	12	6	5	7
Count 1	8	5	9	5	5	7	11	12
Count >=1	12	7	13	7	11	17	18	16
f(1)	35%	22%	39%	22%	22%	30%	48%	52%
f(3)	9%	4%	9%	4%	13%	9%	4%	4%
f(5)	4%	4%	4%	4%	13%	17%	13%	13%
f(7)	4%	0%	4%	0%	0%	17%	13%	0%
f(9)	0%	0%	0%	0%	0%	0%	0%	0%
1/3	9%	22%	13%	26%	0%	22%	13%	17%
1/5	26%	17%	13%	26%	39%	4%	4%	13%
1/7	13%	26%	17%	4%	13%	0%	4%	0%
1/9	0%	4%	0%	13%	0%	0%	0%	0%
sum	100%	100%	100%	100%	100%	100%	100%	100%
f >1	17%	9%	17%	9%	26%	43%	30%	17%
f <1	48%	70%	43%	70%	52%	26%	22%	30%
f 1	35%	22%	39%	22%	22%	30%	48%	52%
f >= 1	52%	30%	57%	30%	48%	74%	78%	70%
sum	100%	100%	100%	100%	100%	100%	100%	100%

For example, question #5, with description of “HVAC/Mech Equipment” means “what is the importance of HVAC versus Mechanical Equipment with respect to the Mechanical Infrastructure condition?”. In addition, the frequency of each input (e.g f(1)) and input category is recorded. The average input values for each question are calculated and are compared with the frequencies in an attempt to rationalize the answers and make sense of the respondent’s logic. In general the average value is close to that of the group with the highest frequency.

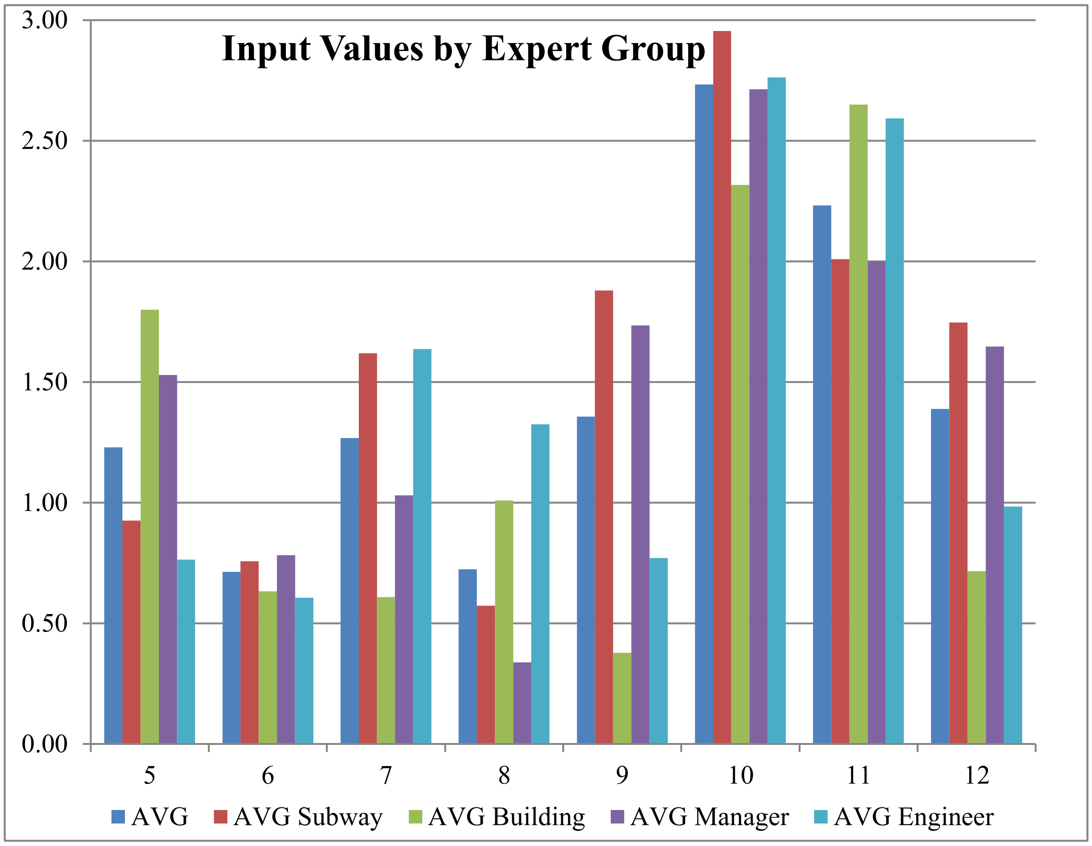


Figure 4.6 Sample Input Data by Expert Group (Questions 5 – 12)

Additionally, based on the previously defined respondent categories, the average input values are studied to check the effect and variations of input with the respondent’s background as seen in Figure 4.6 for questions 5 – 12. Overall, the answers of subway-related experts and respondent's with managerial-level experience are close to the average values, which is satisfactory since the model is mainly to be used by these categories.

4.5 Case Study

A case study of the developed methodology is conducted on Athens, Greece metro system. Construction of the network begun in 1991 and the first part was delivered in 2000 when the operation started. Athens' subway system is among the newest in the world and is considered as a state-of-the-art project for its construction, its contribution in the local community and the overall efficiency. It is widely renowned for the fascinating archeological exhibits at its stations, especially in the downtown and old town areas. Thanks to the metro excavation works, an area of around 79,000 m^2 brought to light almost 50,000 findings of high archeological value. Nowadays, the metro system consists of 2 subway lines and 41 stations in a total of 79.8 kilometers. The commuter load of the metro system reaches around 938,000 daily passengers and in combination with the ground urban railway that serves 415,000 customers daily, is the city's most vital mean of transportation. At present, construction works are taking place for the expansion of the existing system with 6 stations. The addition of a new "U-shaped" line with a total length of 33 kilometers and 34 stations that will serve 500,000 passengers daily and an estimated cost of 3.3 billion Euros (€) is going to start in the near future. As stated earlier, the metro system is quite new; therefore the authorities are not facing the need to develop a methodology to evaluate the infrastructure performance and plan repair activities accordingly. The organization consists of well-defined divisions (structural, communications, track work, power supply) and each division complies with the maintenance guidelines and does routine inspections. Client service-regarding annual surveys are performed, to determine the Customer Satisfaction Index (CSI) and the European Passenger Satisfaction Index (EPSI). The track-work department ranks its performance according to the European Foundation of Quality Management (EFQM).

For the purposes of a case study, a sub-network of the initial system that started operation in 2000 is used. Two separate subway lines are included and there are two subway stations in each line. There is an intersection of these lines and the hub-station is considered as one of the studied, so there are three metro stations in total. Tunnels are not considered as there were no data available in the time of data collection. Evaluations of defects come directly from the inspection reports of the authority's engineers. They evaluate the components on a 1-5 scale which allows a simple analogical transformation to the 5-step A-E scale proposed in this research.

4.6 Summary

The required data for the model development are collected through questionnaires. An on-line survey was designed allowing the users to select their preferred answers with a simple click. The Metro Network Performance website is also presented as the created platform to accommodate the survey, where respondents can find the description of the project and its scope, along with the survey completion guidelines. The raw data from the questionnaires are retrieved manually and inserted in spreadsheets for further processing and calculations.

5 Model Implementation and Case Study

5.1 Introduction

In this chapter, the implementation of the developed methodology is presented. The first part displays the calculation of weights used in the model, both defect and component weights and a relative analysis. After calculating the final weights, the model is set to be used in a case study. Consequently, in the next part, the methodology is implemented on an actual subway network to exploit its capabilities. Step-by-step, at first the subway component condition is evaluated, followed by the calculation of stations and tunnels, until climbing all the way upwards the subway network hierarchy, namely lines and network condition. Finally the model is validated by comparison of the results with existing reports on the case study. The flowchart of the Model Implementation stage can be seen in Figure 5.1.

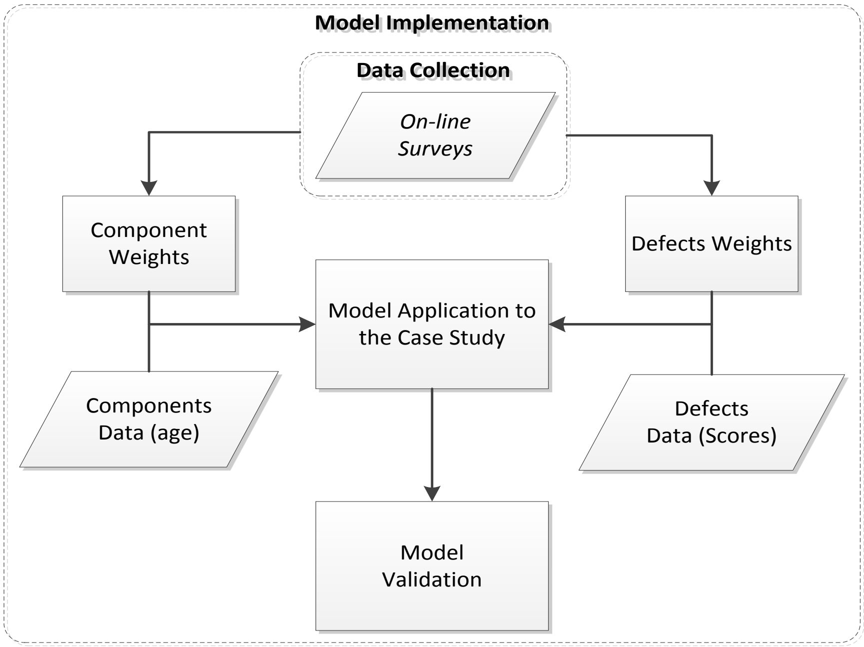


Figure 5.1 Model Implementation Flowchart

5.2 Relative Importance Weights

Data for the determination of weights originate from the responses to the on-line survey presented in Chapter 4. A total of 23 responses are used in the calculation process. Defect weights are extracted with the use of AHP while component weights are defined through the implementation of ANP. The final obtained weights to be used in the model are illustrated and discussed in the following sections.

5.2.1 Defect Weights

A straightforward application of AHP makes the calculation of defect weights possible. In the following tables the eventual acquired defect weights appropriate for the component condition index calculation are shown.

5.2.1.1 Electrical Defect Weights

In Table 5-1, the defects of the electrical components can be seen.

Table 5-1 Electrical Component Defect Weights

Component	Defect	Weight
Distribution Cables	INSULATION	0.222
	VOLTAGE	0.269
	SERVICE INTERRUPTION	0.509
Panels/ Transformers	CORROSION	0.175
	OVERHEATING	0.364
	SERVICE INTERRUPTION	0.461
Lightning System	OVERHEATING	0.465
	FLICKERING	0.298
	EXCESSIVE NOISE	0.237
Emergency Lightning	OVERHEATING	0.658
	EXCESSIVE NOISE	0.342

Table 5-2 Mechanical Component Defect Weights

Component	Defect	Weight
Pipes	CORROSION	0.168
	LEAKING	0.347
	CRACKING	0.486
Ducts	DIRT/RUST	0.337
	LEAKING	0.370
	INSULATION	0.294
Boilers/ Chillers	CORROSION	0.153
	EXCESSIVE NOISE	0.161
	OVERHEATING	0.333
	LEAKING	0.353
Air Handling Units	DIRT/ MOLD/ RUST	0.650
	EXCESSIVE NOISE	0.350
Track Drainage	DRAINS DAMAGE	0.213
	FLOODING	0.445
	CLOGGING	0.342
Fire Extinguish	CORROSION	0.409
	LEAKING	0.591
Elevators	ALIGNMENT	0.284
	VIBRATION	0.272
	SPEED LOSS	0.194
	CORRESPONDENCE	0.250
Escalators	MECHANICAL DAMAGE	0.764
	SPEED LOSS	0.236

In the case of distribution cables, “service interruption” is the most important defect with a weight of 51% which makes sense since any pause in the continuous power service through the cables affects the entire electrical infrastructure not only the wiring system itself. The remaining defects namely “voltage” and “insulation” share an almost equal contribution the cables condition. Similar results are obtained for distribution panels and transformers where “service interruption” possesses a weight of 46%, followed by “excessive heating” with 36.5%. “Corrosion” is rather unimportant compared with the rest. “Overheating” turns out to be the most important defect for lightning and emergency lightning components weighting 46.5% and 66% respectively because it can lead to total damage of the components. “Flickering” and “excessive noise” seem to be less definitive. Overall it can be concluded that “overheating” when existing, is a very important defect for electrical components and should be evaluated carefully and always be prevented.

5.2.1.2 Mechanical Defect Weights

In Table 5-2, the defects of the mechanical components are illustrated. “Cracking” with 49% and “leaking” with 35% are the most critical defects affecting pipe performance as their presence can compromise the water flow in the buildings and even cause problems in the structural parts. In the case of ducts, weights are distributed almost equally among the three defects. “Leaking” and “overheating” with 35% and 33% are the most significant factors for boilers, while the presence of “dirt/ mold/ rust” (65%) occurs to be the principal deficiency of air-handling units since it is causing unhealthy and maybe dangerous air circulation in the metro system. The track drainage system is mostly affected by the symptom of “flooding” (45%) which can cause operational but also safety issues in the subway network infrastructure. “Leaking” (59%) is a crucial shortcoming of fire extinguishing systems, since constant leakage can cause permanent structural problems to the building as in the case of pipes, whereas “corrosion” (41%) creates obstacles in the proper function when needed. Elevators are directly influencing client service so defects such as “correspondence” (25%) and “vibration” (27%) dominate. On the other hand “alignment” (29%) although not really making an impact when small, it may cause larger mechanical problems. Finally, escalators’ main concern is the “mechanical damage” (76%) flaws that can interrupt or make unsafe the transportation of people instead of “speed loss” (24%) that only cause some level of inconvenience.

5.2.2 Component Weights

The component weights are calculated with the use of the ANP as explained in the model development stage and in the literature review. The ANP is chosen for its ability to reflect the interdependency among the structural, electrical and mechanical infrastructure of subway systems. A sample of ANP super matrixes can be seen in the Appendix.

5.2.2.1 Stations Component Weights

At first, the weights of components for subway stations are presented. They are different than the ones of subway tunnels since the components themselves are not the same in both cases.

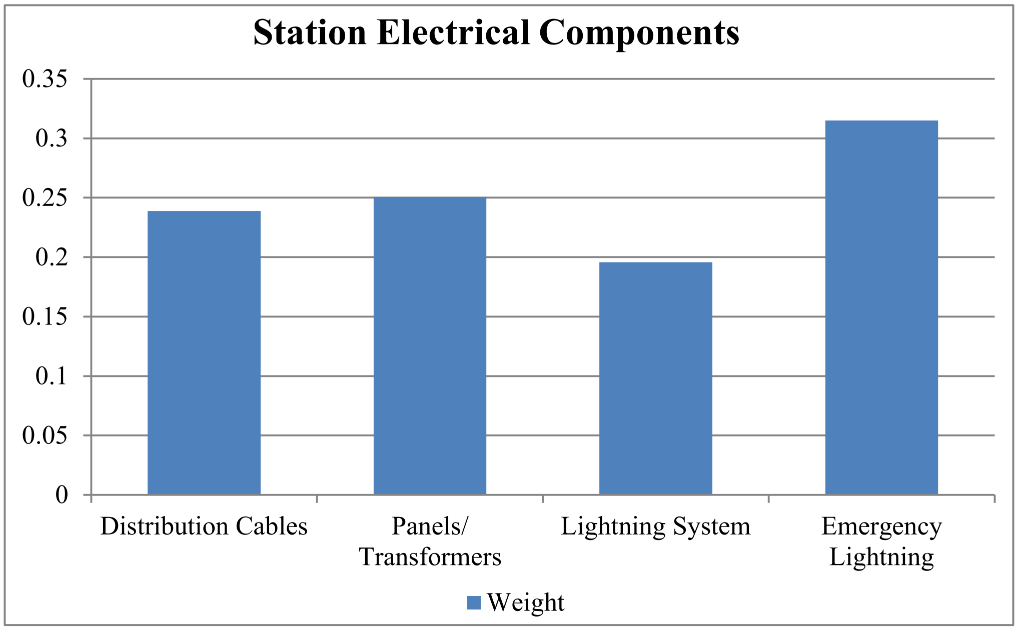


Figure 5.2 Station Electrical Component Local Weights

As it comes out from Figure 5.2, “Emergency Lightning” component is the most critical for the electrical infrastructure of a subway station with a relative importance weight of 31.4%. Its direct connection with public safety in urgent situations justifies this result. “Panels/ Transformers” and “Distribution Cables” follow with almost equal weights, 25% and 24% respectively.

According to Figure 5.3, “Escalators” with a weight of 29% and “Elevators” with 20% are unambiguously the most important elements of subway stations mechanical operation. Escalators score a higher weight than elevators, since practically every passenger uses them and can serve as the only alternative for impaired people in case of elevator failure. The “Fire Extinguish” component is vital for commuter safety so it is the other one that can be distinguished, recording a weight of around 14%.

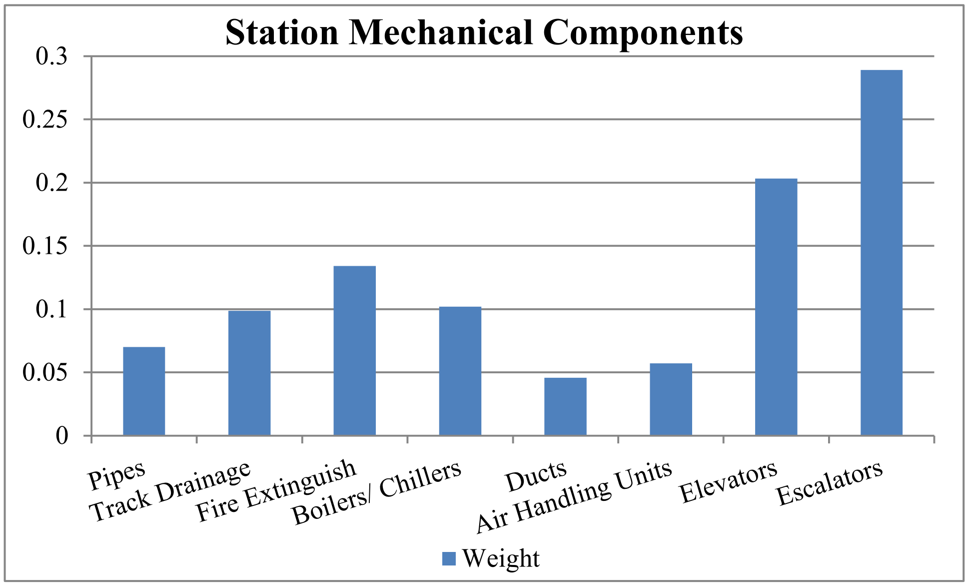


Figure 5.3 Station Mechanical Component Local Weights

A "concentration" of importance can be noticed for components that belong in the "Mechanical Systems" component group in comparison to "Mechanical Equipment" and "HVAC" groups. This is exactly why the extra level of hierarchy in mechanical infrastructure was added. The explanation behind these results lies to the two following facts:

- The group of "Mechanical Systems" consists of only two components, namely elevators and escalators, whereas the others have three components each.
- The localized weight of "Mechanical Systems" is the highest in that hierarchy level.

Figure 5.4 shows the distribution of Mechanical component group weights.

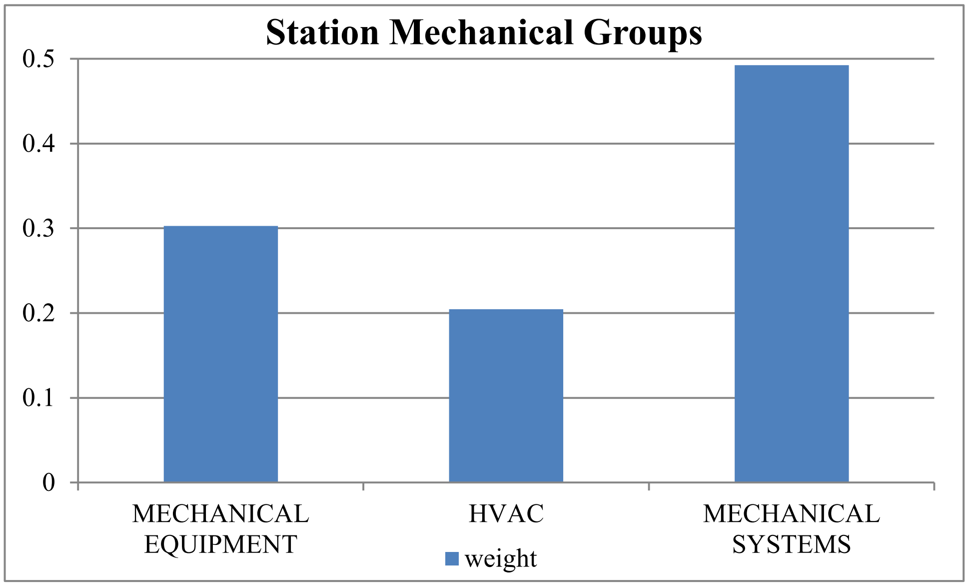


Figure 5.4 Station Mechanical Component Group Local Weights

The last step of weights, produced from the ANP pairwise comparison matrixes are the importance weights of the different type of infrastructure, explicitly structural, electrical and mechanical. Figure 5.5 discloses them. "Mechanical" infrastructure turns out to be the most crucial infrastructure type of subway networks. Perhaps the fact that is mostly associated with customer service and public safety can rationalize this outcome.

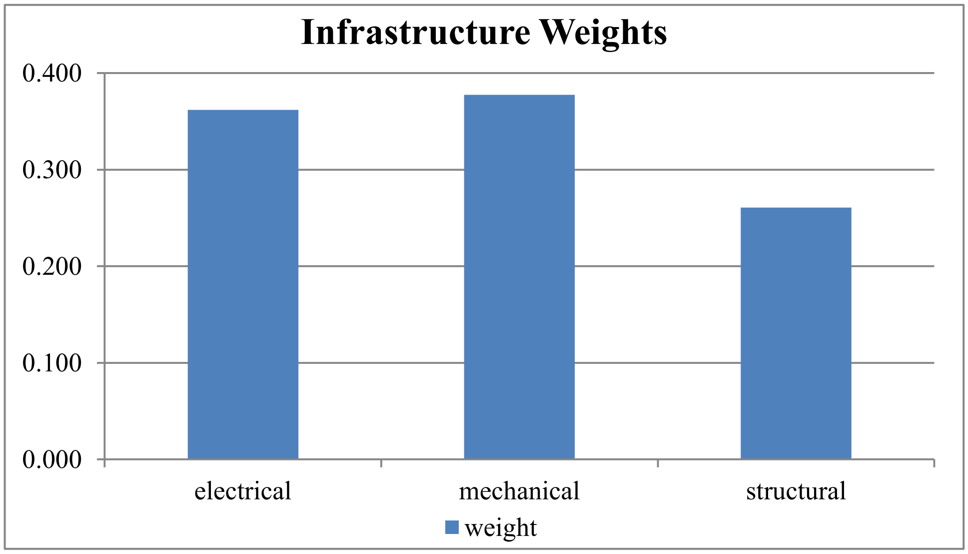


Figure 5.5 Infrastrure Weights

After implementation of the last steps of ANP, the final global decomposed weights that derive from the limiting super matrix are illustrated in Table 5-3. These are the weights that are proposed by this research and used in the model implementation.

Table 5-3 Global Station Components Weights

Division	Component	Weight (%)
ELECTRICAL	Distribution Cables	8.6
	Panels/ Transformers	9.1
	Lightning System	7.1
	Emergency Lightning	11.4
MECHANICAL	Pipes	2.6
	Track Drainage	3.7
	Fire Extinguish	5.1
	Boilers/ Chillers	3.8
	Ducts	1.7
	Air Handling Units	2.2
	Elevators	7.7
	Escalators	10.9
STRUCTURAL		26.1

In a nutshell, components affecting client service such as “Escalators” or “Elevators” and components responsible for public safety such as “Fire Extinguish” and “Emergency Lightning” achieve the highest importance of the total subway station infrastructure.

5.2.2.2 Subway Tunnels Component Weights

Information for the determination of tunnel component weights originates from the same questions used for the stations. Stations comprise of the same components as tunnels plus some additional. That permits the faster tunnel weight calculations with the usage of a normalization method.

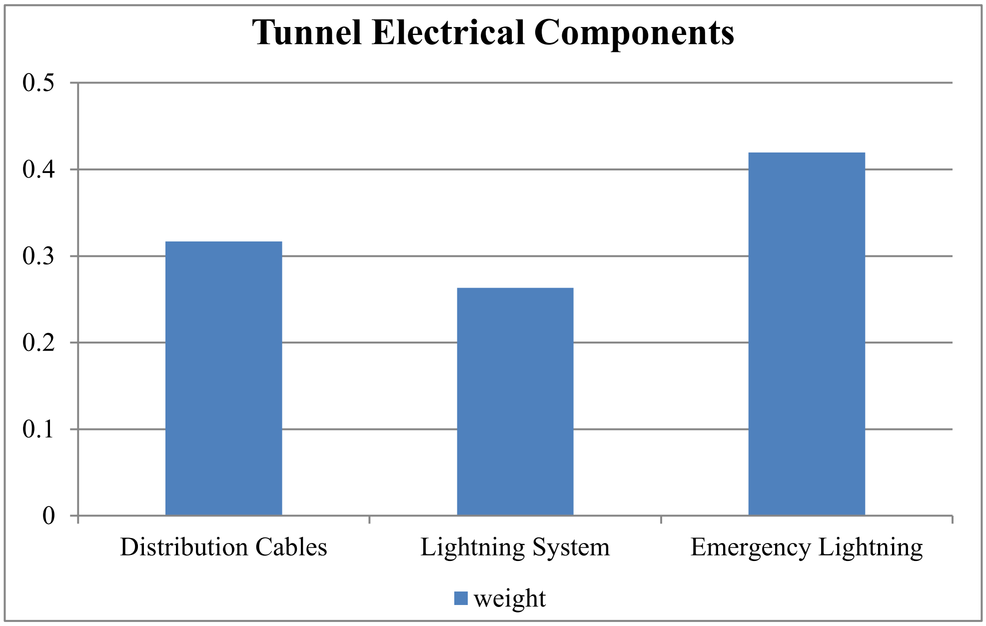


Figure 5.6 Tunnel Electrical Component Local Weights

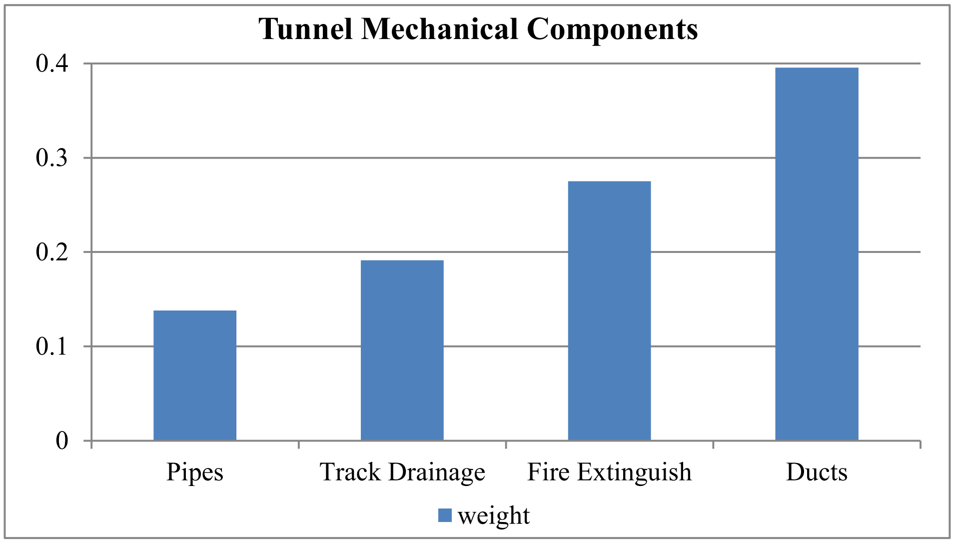


Figure 5.7 Tunnel Mechanical Component Local Weights

As seen in Figure 5.6, the “Emergency Lightning” component is the most important part of the electrical infrastructure of tunnels, weighting 42%. That is a logical finding, since illumination needs are low in subway tunnels unless there is an urgent situation which is the purpose of the existence of this specific component, to guide operators and passengers safely.

From Figure 5.7 it can be summarized that “Ducts” with a weight of 39% are the most prominent component, been responsible for the proper ventilation not only of tunnels but also affect the air quality in the station area. Right afterwards, “Fire Extinguish” ranks recording a weight of 28% and the reasons are apparent. It is the protective measure in case of a fire emergency and in collaboration with the air flow and ventilation of ducts, it ensures public safety.

Again, as in the case of subway stations, the extra hierarchy level of mechanical components group is affecting this outcome since is the single “HVAC” component in tunnels when “Mechanical Equipment” is represented by all three of its components. HVAC has a weight of 39% and Mechanical equipment weighs the remaining 61%. In Table 5-4 the average global tunnel component weights used for the STREM (STRuctural/Electrical/Mechanical) calculations are demonstrated.

Table 5-4 Global Tunnel Component Weights

Division	Component	Weight (%)
ELECTRICAL	Distribution Cables	11.4
	Lightning System	9.5
	Emergency Lightning	15.1
MECHANICAL	Pipes	5.1
	Track Drainage	7.1
	Fire Extinguish	10.2
	Ducts	14.7
STRUCTURAL		26.9

5.2.3 Statistical Analysis

Data for computations of defect and component weights are collected through questionnaires. A total number of 23 complete responses was received. The final global weights used in the STREM model methodology are representing the average obtained weight values from the respondents. A statistical analysis is performed to check the nature and validity of these responses. A summary of some statistical values for the defect weights are illustrated in Table 5-5 and Table 5-6. They include the mean value of weights, the standard deviation and the lower and upper values for a 95% confidence level.

Table 5-5 Electrical Defects Statistical Analysis

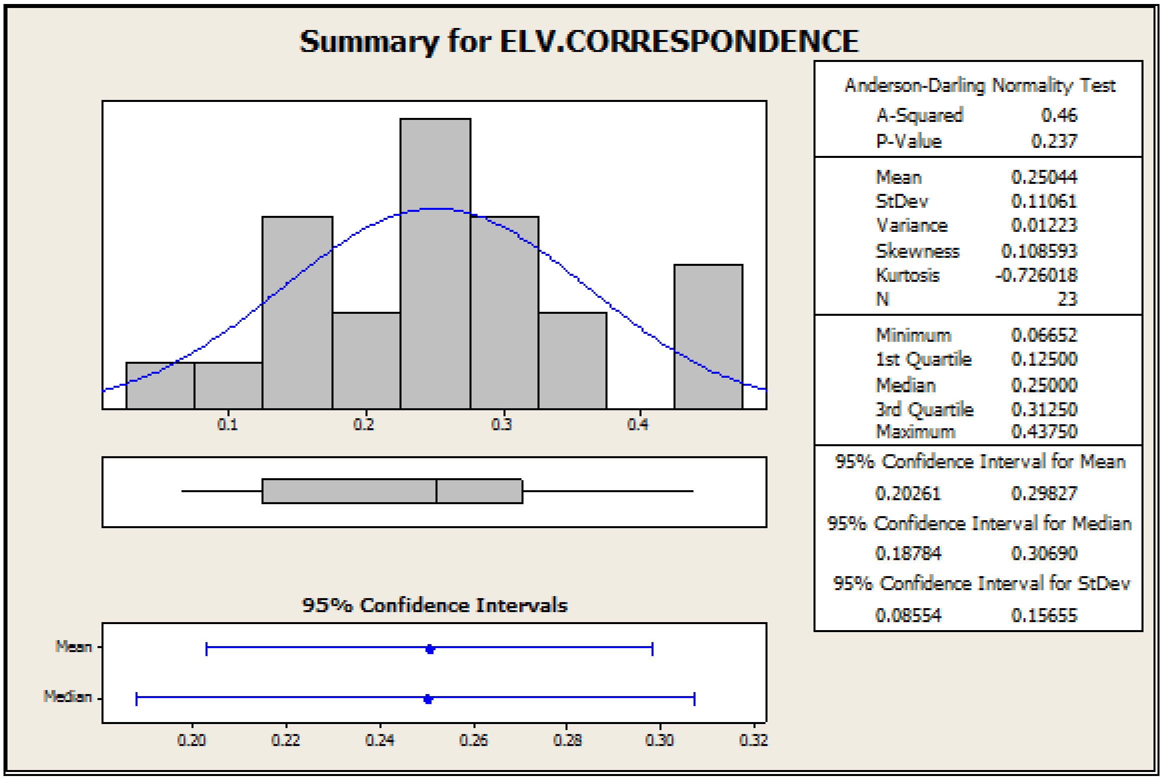
Component	Defect	Mean	Standard Deviation	95% Lower	95% Upper
Distribution Cables	Insulation	0.222	0.157	0.154	0.290
	Voltage	0.269	0.171	0.196	0.343
	Service interruption	0.509	0.192	0.426	0.591
Panels/ Transformers	Corrosion	0.175	0.159	0.106	0.243
	Overheating	0.364	0.135	0.306	0.423
	Service interruption	0.461	0.143	0.399	0.523
Lightning System	Overheating	0.465	0.242	0.360	0.569
	Flickering	0.298	0.172	0.224	0.372
	Excessive Noise	0.237	0.118	0.186	0.289
Emergency Lightning	Overheating	0.658	0.249	0.550	0.765
	Excessive Noise	0.342	0.249	0.235	0.450

The statistical analysis revealed that many of the calculated weights possess high standard deviation values. This can be somehow expected since the weights are a product from expert opinions. Considering the difference in the mentality and approaches from people, even expert personnel cannot always agree. Overall though, apart from some exceptions of course, the range of the maximum and minimum observed weight values is not very wide.

Table 5-6 Mechanical Defects Statistical Analysis

Component	Defect	Mean	Standard Deviation	95% Lower	95% Upper
Pipes	Corrosion	0.168	0.106	0.122	0.214
	Leaking	0.347	0.165	0.275	0.418
	Cracking	0.486	0.144	0.424	0.548
Ducts	Dirt/ Rust	0.337	0.221	0.241	0.432
	Leaking	0.370	0.207	0.280	0.460
	Insulation	0.294	0.150	0.229	0.358
Boilers	Corrosion	0.153	0.108	0.107	0.200
	Excessive noise	0.161	0.113	0.112	0.209
	Overheating	0.333	0.108	0.286	0.380
	Leaking	0.353	0.118	0.302	0.404
Air Handling Units	Dirt/ Rust/ Mold	0.650	0.242	0.545	0.755
	Excessive noise	0.35	0.242	0.245	0.454
Track Drainage	Drains damage	0.213	0.183	0.134	0.292
	Flooding	0.445	0.183	0.366	0.524
	Clogging	0.342	0.122	0.289	0.395
Fire Extinguish	Corrosion	0.409	0.251	0.301	0.518
	Leaking	0.591	0.250	0.482	0.699
Elevators	Alignment	0.284	0.165	0.213	0.355
	Vibration	0.272	0.163	0.202	0.342
	Speed loss	0.194	0.118	0.143	0.245
	Correspondence	0.250	0.111	0.203	0.298
Escalators	Mechanical damage	0.764	0.148	0.701	0.828
	Speed loss	0.236	0.148	0.172	0.299

The statistical analysis was done with the use of Minitab statistical software. A snapshot of the results in the case of the correspondence defect of elevators is shown in Figure 5.8.



Anderson-Darling Normality Test	
A-Squared	0.46
P-Value	0.237
Mean	0.25044
StDev	0.11061
Variance	0.01223
Skewness	0.108593
Kurtosis	-0.726018
N	23
Minimum	0.06652
1st Quartile	0.12500
Median	0.25000
3rd Quartile	0.31250
Maximum	0.43750
95% Confidence Interval for Mean	
0.20261	0.29827
95% Confidence Interval for Median	
0.18784	0.30690
95% Confidence Interval for StDev	
0.08554	0.15655

Figure 5.8 Elevators Correspondence Statistical Analysis

Another analysis is performed in the following section, discussing the results and attempting to interpret the outcomes and their variances.

5.2.4 Weights Analysis and Discussion

As explained in the Data Collection chapter, the respondents can be classified in 2 ways. The first is based on their infrastructure experience, whether it is subway/rail/transit related or building related. The second split is based on the position and responsibility level, namely managerial experience or engineering level. The obtained weights were grouped accordingly and a comparative analysis was conducted and is presented in the following tables.

Table 5-7 Respondent Groups Component Weights

Component	Overall	Subway	Building	Manager	Engineer
Distribution Cables	8.6%	9.8%	6.6%	10.1%	6.5%
Panels/ Transformers	9.1%	8.1%	10.8%	8.6%	9.7%
Lightning System	7.1%	7.4%	6.5%	6.9%	7.4%
Emergency Lightning	11.4%	11.3%	11.5%	12.0%	10.5%
Pipes	2.6%	3.1%	1.8%	1.8%	3.9%
Track Drainage	3.7%	3.3%	4.5%	3.3%	4.3%
Fire Extinguish	5.1%	5.8%	3.7%	5.4%	4.6%
Boilers	3.8%	3.6%	4.4%	4.8%	2.5%
Ducts	1.7%	1.2%	2.7%	1.9%	1.5%
Air Handling Units	2.2%	1.6%	3.2%	2.7%	1.4%
Elevators	7.7%	9.7%	3.9%	8.3%	6.7%
Escalators	10.9%	9.4%	13.7%	10.1%	12.1%

In order to better explore the variance in the results seen in Table 5-7, the percentage differences of the retrieved respondent group weights are calculated and shown in drawn in a graph shown in Table 5-8.

Table 5-8 Respondents Group Weight Difference

Component	Dif. ovrl-subway	Dif. ovrl-building	Dif. ovrl-manager	Dif. ovrl-engineer
Distribution Cables	-13%	24%	-16%	24%
Panels/ Transformers	11%	-19%	5%	-7%
Lightning System	-4%	8%	3%	-5%
Emergency Lightning	0%	-1%	-5%	8%
Pipes	-16%	30%	32%	-46%
Track Drainage	11%	-20%	11%	-16%
Fire Extinguish	-15%	27%	-7%	10%
Boilers	7%	-13%	-24%	36%
Ducts	32%	-59%	-11%	16%
Air Handling Units	27%	-50%	-24%	35%
Elevators	-27%	49%	-9%	13%
Escalators	14%	-25%	7%	-11%
STRUCTURAL	1%	-2%	7%	-11%

Looking in the results of the previous tables, it can be noted that excessive variances exist between the obtained weights. A deeper observation though, displays that "subway related" experts score a closer final weight to the average one than the "building related" individuals. Furthermore, in the second classification, "manager level" weights seem to achieve similar to the average results compared to the "engineer level". The conclusion from these remarks is quite encouraging because the most desirable "opinions" –if something like that can be said- and the final decisions come from this group of experts. Therefore it is satisfactory that the final weight values to be used in the model, obey their commands. The graph in Figure 5.9 provides a visual explanation of this discussion.

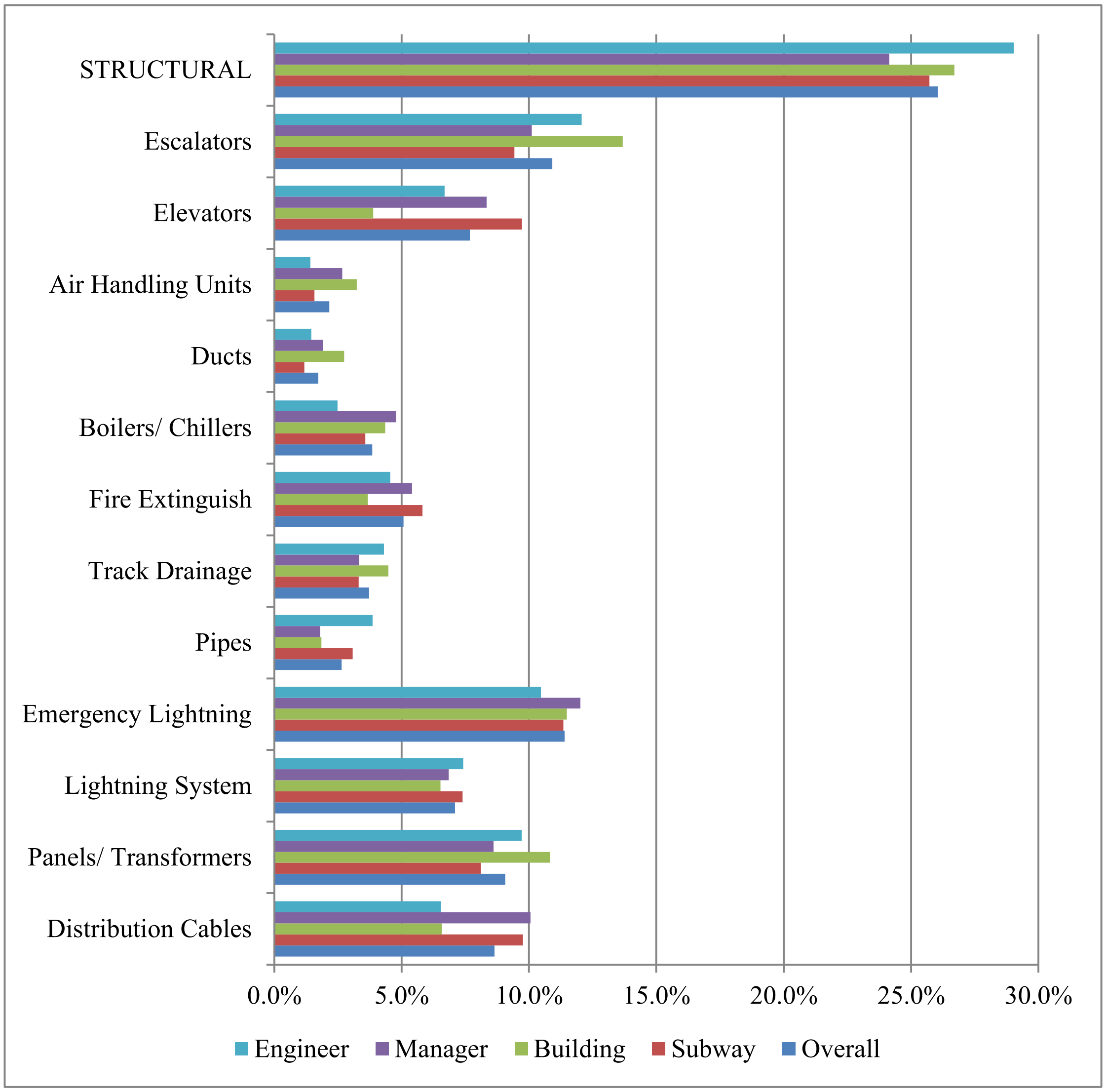


Figure 5.9 Expert Group Component Weights

Similar analysis has been conducted for the weights of defects as well as for all the other levels of the subway network hierarchy. They are presented in the appendix.

5.3 Model Implementation to the Case Study

In order to exploit the full potential of the developed methodology, the model is implemented on a partial network of Athens, Greece metro system. General information about the metro system is provided in chapter 4. A recreation of the sub-network is shown in Figure 5.10. For confidentiality reasons, the names of the stations are not uncovered. Code names such as Line 1 and Station A are used.

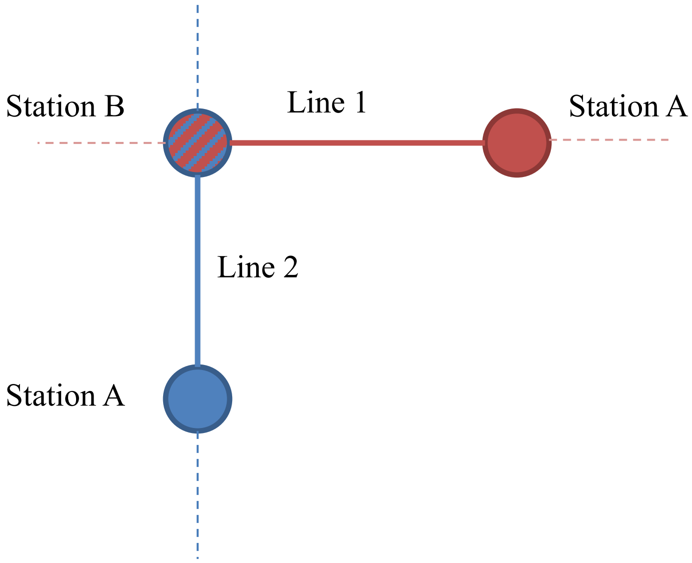


Figure 5.10 Sub-network Diagram

5.3.1 Component Condition

The model starts by calculating the condition of the components and then continues to the remaining levels of the subway network hierarchy. In Table 5-9 a typical defects evaluation table is shown.

Table 5-9 Line 1 Station A Defects Evaluation Table

ELECTRICAL			MECHANICAL		
Component	**Defect**	**SCORE**	**Component**	**Defect**	**SCORE**
Distribution Cables	INSULATION	B	**Boilers**	CORROSION	B
	VOLTAGE	B		EXCESSIVE NOISE	B
	SERVICE INTERRUPTION	B		OVERHEATING	B
Panels/ Transformers	CORROSION	B		LEAKING	B
	OVERHEATING	B	**Air Handling Units**	DIRT/ MOLD/ RUST	C
	SERVICE INTERRUPTION	B		EXCESSIVE NOISE	C
Lightning System	OVERHEATING	B	**Track Drainage**	DRAINS DAMAGE	B
	FLICKERING	B		FLOODING	B
	EXCESSIVE NOISE	B		CLOGGING	B
Emergency Lightning	OVERHEATING	B	**Fire Extinguish**	CORROSION	B
	EXCESSIVE NOISE	B		LEAKING	B
MECHANICAL			**Elevators**	ALIGNMENT	B
Pipes	CORROSION	B		VIBRATION	B
	LEAKING	B		SPEED LOSS	B
	CRACKING	B		CORRESPONDENCE	B
Ducts	DIRT/RUST	C	**Escalators**	MECHANICAL DAMAGE	B
	LEAKING	C		SPEED LOSS	B
	INSULATION	C			

In Table 5-10, the entire implementation of the customized TOPSIS technique is displayed for the calculation of the condition index of duct for Station A in Line 1.

In Figure 5.11, a graph with the performance of all components of Station A in Line 1 is illustrated.

Table 5-10 Line 1 Station A Ducts Condition Index

Defect Weight	Dirt/Rust 0.337	Leaking 0.370	Insulation 0.294		Positive Closeness Si+			Average
Ducts condition	5.167	5.167	5.167	Si+	0.021	0.025	0.016	0.249
Ideal	10.000	10.000	10.000		0.000	0.000	0.000	0.000
Worst	0.000	0.000	0.000		0.089	0.108	0.068	0.516
r	11.256	11.256	11.256					
	Normalized rij				Negative Closeness Si-			Average
Ducts condition	0.459	0.459	0.459	Si-	0.024	0.029	0.018	0.266
Ideal	0.888	0.888	0.888		0.089	0.108	0.068	0.515
Worst	0.000	0.000	0.000		0.000	0.000	0.000	0.000
	Weighted Vij				Ducts condition (0-1)		**Ducts condition (0-10)**	
Ducts condition	0.154	0.170	0.135	Ducts condition	0.517		**5.167**	
Ideal	0.299	0.329	0.261	Ideal	1.000		10.000	
Worst	0.000	0.000	0.000	Worst	0.000		0.000	

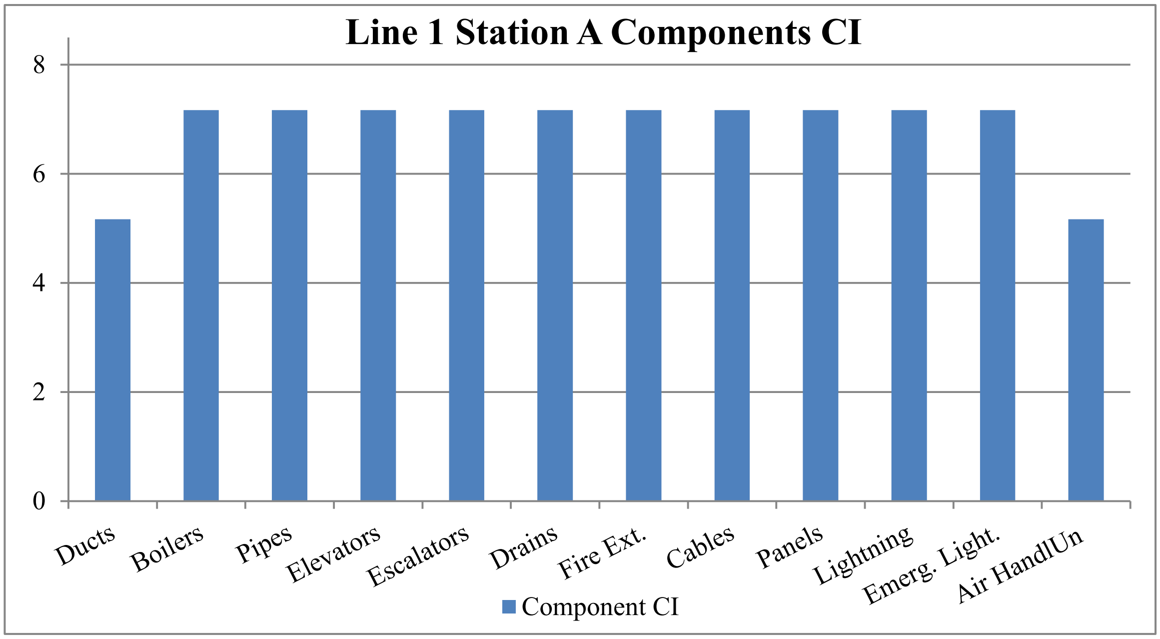


Figure 5.11 Line 1 Station A Components Condition Index Graph

A first look at the station's components performance shows that most of them are in good condition, scoring a CI of 7.167. Two components seem to be in more advanced deterioration, the Ducts and the Air Handling Units which achieve a CI of only 5.167.

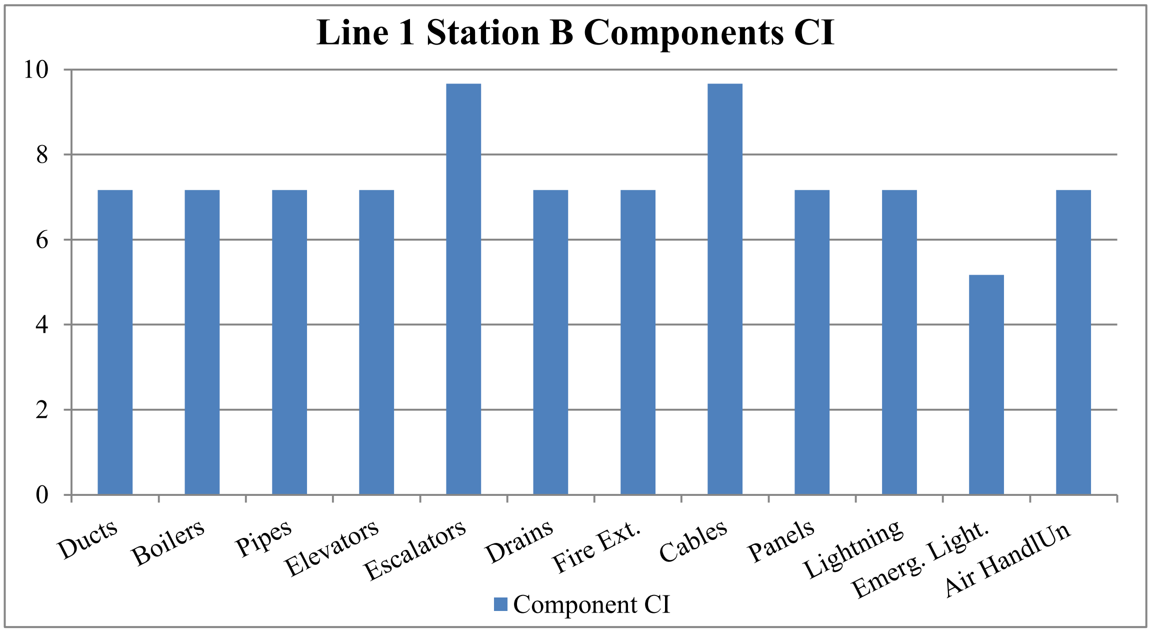


Figure 5.12 Line 1 Station B Components Condition Index Graph

In Figure 5.12, the relative graph for Station B in Line 1 is shown. This station turns out to be in better shape than the previous one overall. The Emergency Lightning component with a CI of 5.167 is the only one showing marks of serious condition decline. Finally, as comes out from Figure 5.13, in Station A of Line 2, the components Air Handling Units, Emergency Lightning and Ducts demonstrate a problematic condition.

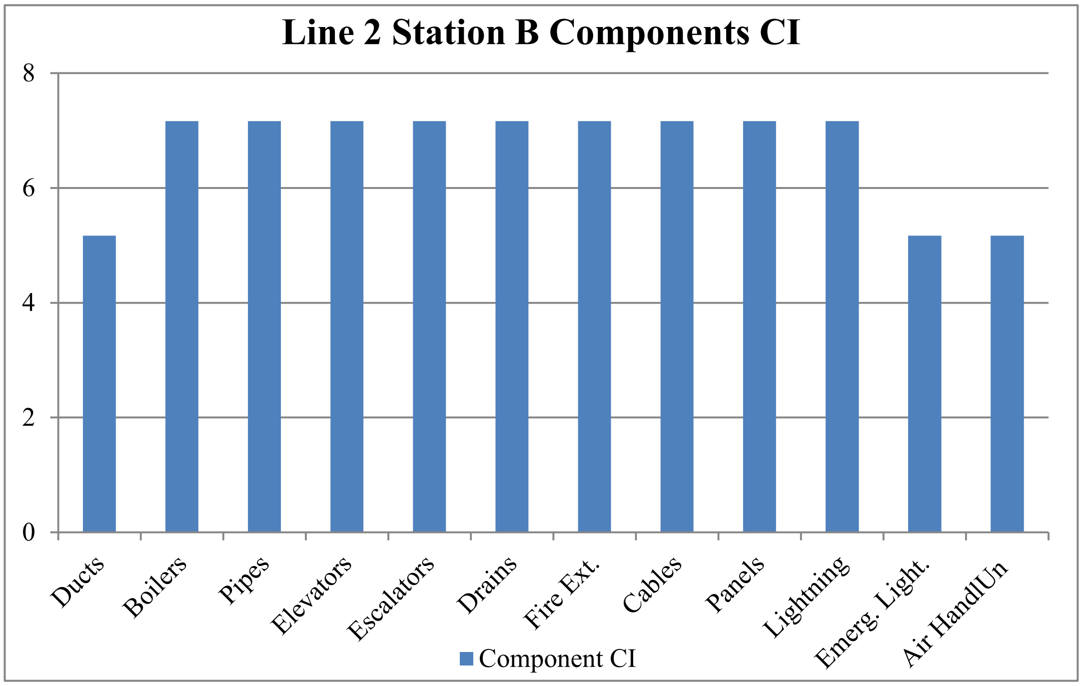


Figure 5.13 Line 2 Station A Components Condition Index Graph

5.3.2 Station Condition

After having obtained the Condition Indexes of all the components in each station, the next step is the calculation of the condition of the stations as one entity. As explained in the methodology, there is the option of having 3 types of results; CI_{el}, CI_{mech} and the integrated STREM. All options are exploited in this section. It has to be mentioned that at this point, the information of structural condition arrives as external input to the model. Structural condition indexes have been calculated for the same case study in a previous research.

In Table 5-11, the analytical computation of the electrical infrastructure condition of Station A in Line 1 is illustrated. Similar tables are produced for all the stations and all the remaining infrastructure types (mechanical and structural).

Table 5-11 Line 1 Station A Electrical Condition Index

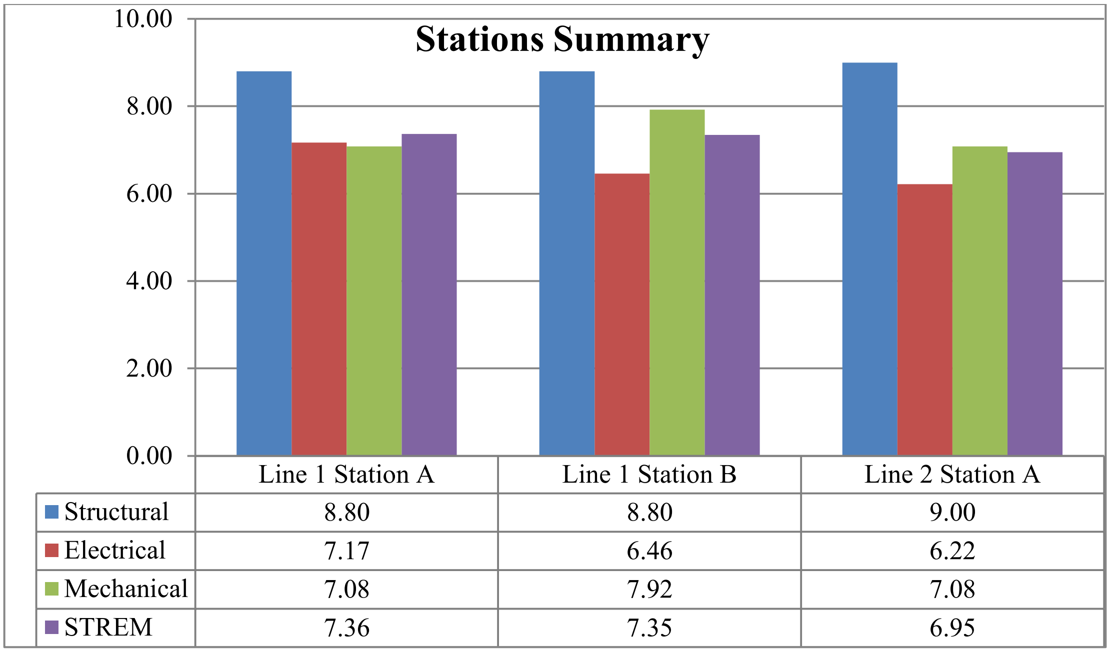
Component Weight	Distribution cables 0.231	Panels/Transformers 0.254	Lightning system 0.191	Emergency lightning 0.324
Station condition	7.167	7.167	7.167	7.167
Ideal	10.000	10.000	10.000	10.000
Worst	0.000	0.000	0.000	0.000
r	12.303	12.303	12.303	12.303
		Normalized rij		
Station condition	0.583	0.583	0.583	0.583
Ideal	0.813	0.813	0.813	0.813
Worst	0.000	0.000	0.000	0.000
		Weighted Vij		
Station condition	0.134	0.148	0.111	0.189
Ideal	0.188	0.207	0.155	0.264
Worst	0.000	0.000	0.000	0.000
Si+		Positive closeness Si+		
0.117	0.003	0.003	0.002	0.006
0.000	0.000	0.000	0.000	0.000
0.414	0.035	0.043	0.024	0.069
Si-		Negative closeness Si-		
0.297	0.003	0.013	0.001	0.004
0.414	0.014	0.030	0.004	0.006
0.000	0.000	0.000	0.000	0.000
	Station condition (0-1)		**Station condition (0-10)**	
Station condition	0.717		**7.167**	
Ideal	1.000		10.000	
Worst	0.000		0.000	

In Table 5-12, the TOPSIS implementation for the calculation of the integrated condition index (STREM) is shown for the case of Station A in Line 1.

Table 5-12 Line 1 Station A STREM

Weight	0.261	0.364	0.375
Infrastructure	structural	electrical	mechanical
Condition	8.8	7.167	7.078
BEST	10	10	10
WORST	0	0	0
r	13.32	12.30	12.25
	Normalized rij		
Condition	0.66	0.58	0.58
BEST	0.75	0.81	0.82
WORST	0.00	0.00	0.00
	Weighted Vij		
Condition	0.172	0.212	0.217
BEST	0.196	0.296	0.307
WORST	0.000	0.000	0.000
Si+	Positive closeness Si+		
0.000551	0.007018	0.008024	0.1248739
0.000000	0.000000	0.000000	0.0000000
0.038282	0.087419	0.093995	0.4687170
Si-	Negative closeness Si-		
0.029646	0.044899	0.047092	0.3487645
0.038282	0.087419	0.093995	0.4687170
0.000000	0.000000	0.000000	0.0000000
	Station condition (0-1)		**Station condition (0-10)**
Station condition	0.736		**7.36**
Ideal	1		10
Worst	0		0

Station A from Line 1 achieves a STREM index of 7.36. Similar tables are constructed for all the remaining stations. In Figure 5.14, a graphical summary of the estimated condition indexes of all the stations of the examined sub-network are shown. In general, although the metro system as discussed previously is quite “young”, the stations infrastructure does not perform excellent. The structural part is the exception, as expected, since the life cycle of structural components is longer than the corresponding electrical and mechanical. On the other hand, still the rating has not entered the critical zone yet, meaning that none of the components or stations yields for immediate intervention actions to improve the current state.



	Line 1 Station A	Line 1 Station B	Line 2 Station A
🟦 Structural	8.80	8.80	9.00
🟥 Electrical	7.17	6.46	6.22
🟩 Mechanical	7.08	7.92	7.08
🟪 STREM	7.36	7.35	6.95

Figure 5.14 Stations Summary

As a general rule, components and infrastructures should be scheduled for restoration works before they reach a condition index of 5 out of 10. In any case the ultimate point of immediate action would be a CI of 4 and in that scenario the most probable solution would be rehabilitation or complete replacement, something that would add a considerable cost to the budget.

5.3.3 Subway Line Condition

With all the necessary values of stations been determined, the reliability equations can be implemented for the evaluation of the performance of the subway lines. In Figure 5.15, the plot of Line 1 and Line 2 indexes is presented accompanied by the respective data table.

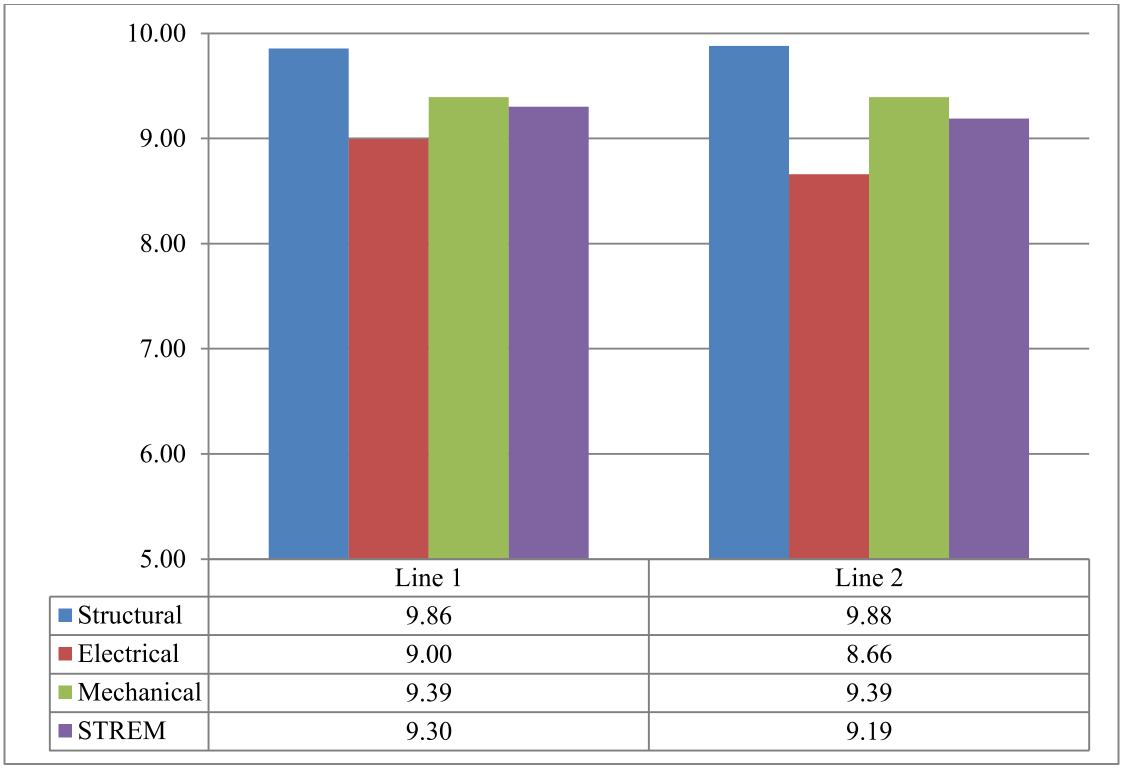


Figure 5.15 Subway Lines Condition

Line 1 achieves a slightly better integrated performance (STREM = 9.30), although both studied lines are in very good shape. Station A of Line 2 is responsible for the slightly decreased condition of the line since it is the station with the lowest overall condition indexes.

5.3.4 Subway Network condition

A subway network comprises of different lines that themselves contain stations and tunnels with a large number of components. After finding the line condition, the following and final step of the condition assessment model is the identification of the subway network condition. With the application of the network reliability-based condition equation, the result for the examined sub-network is seen in Figure 5.16.

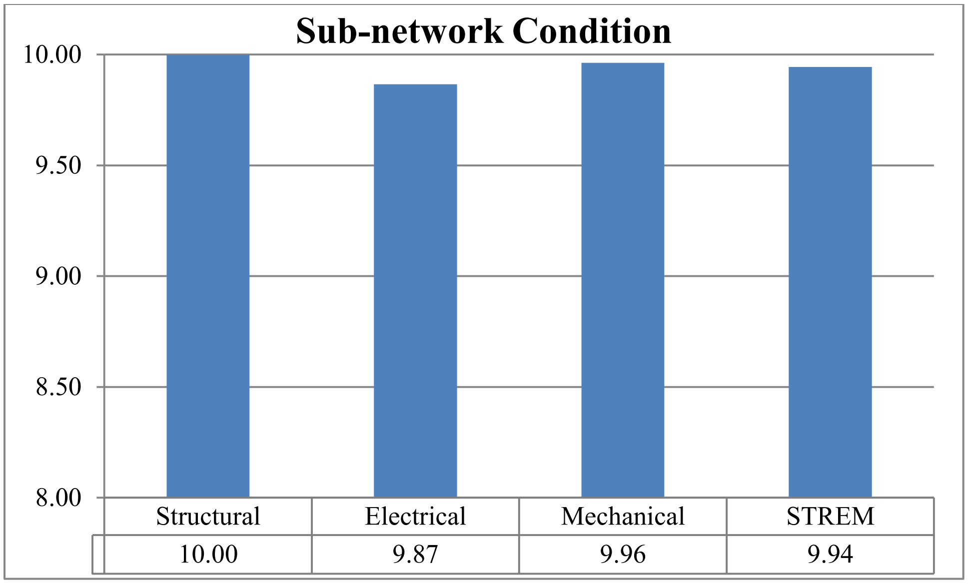


Figure 5.16 Sub-network Condition Indexes

Again, the condition of structural infrastructure achieves excellent results and it can be explained from the longer lifespan of structural elements. Overall the sub-network records near to excellent outcomes for all types of infrastructure and in the case of integrated performance (STREM = 9.94).

In general, it can be noticed that lines and the entire sub-network attain larger CI values than those of their belonging stations and components. First of all, the absence of tunnels in the examined case study, somehow rationalizes this outcome. The fact that tunnel values are not inserted in the reliability-based equations means that the second multiplier of these formulas is missing and consequently, the calculated condition index remains considerably higher than expected since it is affected by the stations ratings only. Another explanation lies in the inherent features of the theory of systems reliability. By default this technique assesses the ability of a system to operate; irrelevant of the actual current performance level, if the system components are functional, then the system itself is granted functional.

5.3.5 Component Condition Prediction

After completion of the condition assessment model, the second model of the developed methodology, namely the condition prediction model, can start. In this stage, deterioration curves are designed to forecast the future performance of the subway system. A Weibull technique is utilized for this purpose. Following the similar pattern as before, the process initiates from the component level and concludes in the network passing through all the intermediate infrastructure levels.

In order to draw deterioration lines by implementing Weibull theory, only two pieces of information are required, the age of the component and its current condition. That makes the technique very advantageous since the data collection and input processes as well as the calculation process are significantly faster and uncomplicated.

In Figure 5.17, the deterioration curve of the component “Elevators” of Station A in Line 1 is seen. The required inputs to draw this line are:

- Construction year is 2000 and inspection year is 2013, so the age is 13 years.
- Current condition is 7.167 as calculated previously.

According to the graph, elevators are in good condition at the present time, but are deteriorating with a progressive rhythm. In year 2020, the condition will already be 3 out of 10. It is compulsory that maintenance or renovation actions are taken renovation between around 2015 and definitely no later than 2019 when the condition will be surpassing the threshold of 4 out of 10. Similar graphs are constructed for all the components of this station and all the components of the other investigated stations of the subway sub-network. The relative graphs can be found in the appendix.

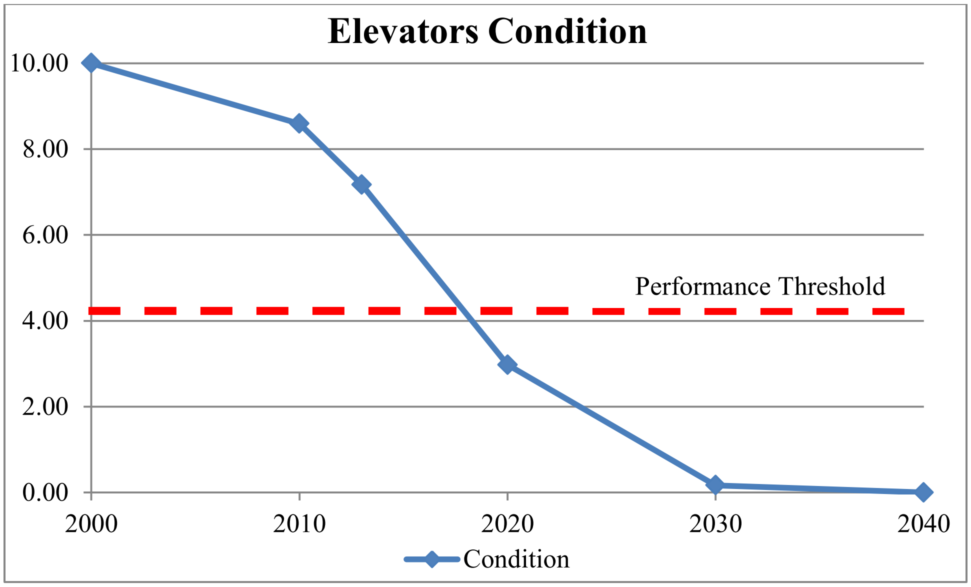


Figure 5.17 Line 1 Station A Elevators Deterioration Profile

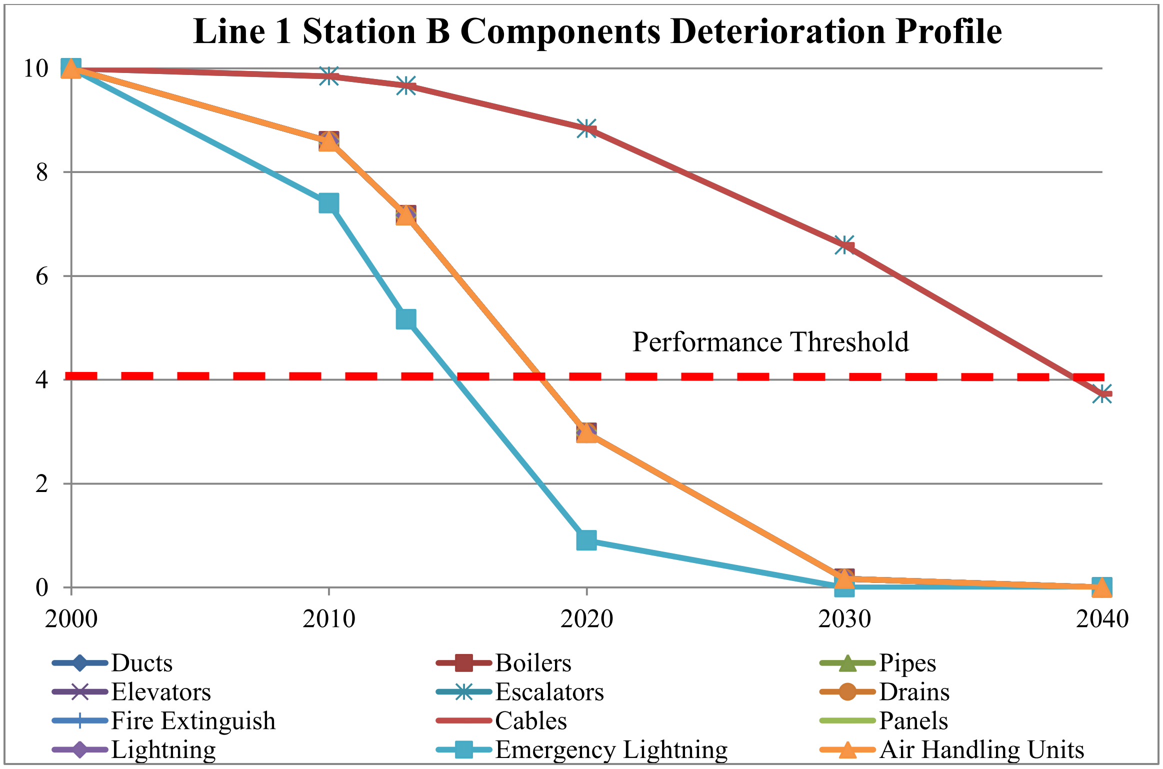


Figure 5.18 Line 1 Station B Components Deterioration Curves

In Figure 5.18, all the component deterioration curves for Station B of Line 1 are displayed. The Emergency Lightning component represented by the blue line, has the most rapid deterioration and should be scheduled for renovation works before 2015. The second batch of components following the orange line is required to be scheduled no later than 2019. Finally, Cables and Escalators with the red line are performing very well and are safe until almost the year of 2040.

5.3.6 Station Condition Prediction

From the deterioration graphs of every component, their future condition can be easily extracted. Based on these extracted values, the entire condition assessment methodology can be repeated for the pre-defined intervals resulting in the calculation of the station condition index at these future points.

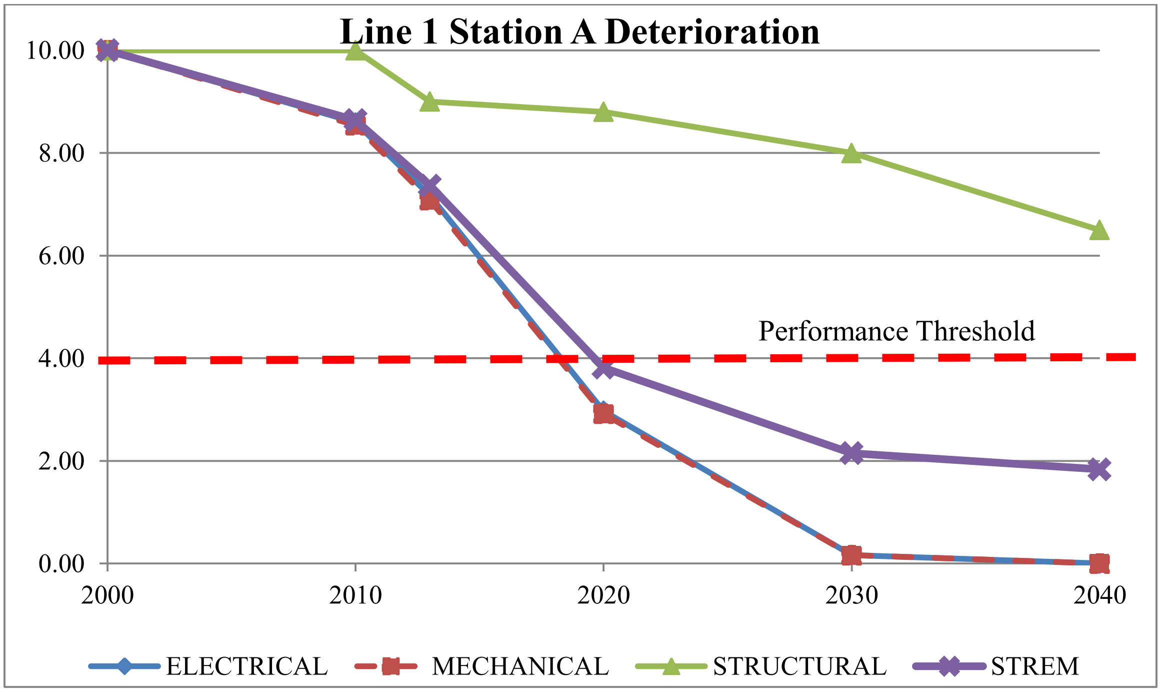


Figure 5.19 Line 1 Station A Deterioration Profile

In Figure 5.19, the deterioration curves of Station A in Line are shown. As it is expected, electrical and mechanical infrastructure deteriorate faster than structural infrastructure. Electrical and mechanical components share similar nominal life expectancies which is why the respecting deterioration lines have very close characteristics, and definitely shorter than that of structural elements. The integrated performance line, represented by the purple line achieves to be close to the curves with the most critical values (electrical and mechanical) while it does not seem to effectively capture the deterioration progress of structural infrastructure. That is acceptable, since it is the critical deterioration lines that are mostly significant and the STREM line seems to be successful in grasping this behaviour. Overall, from this graph, a fierce statement that preventive measures have to be taken before the year 2020 is done. By checking the STREM line, the users of this methodology can have a quick first look about when a rapid decline in the station's condition exist and accordingly they can investigate further to plan repair works. The deterioration graphs of the remaining two stations can be found in the appendix.

5.3.7 Subway Line Condition Prediction

Aggregating the findings from the previous section, the next step is the estimation of the deterioration profiles of the subway lines. The first note that becomes obvious from Figure 5.20 is that after the year 2010, the deterioration of Line 1 begins. In the case of electrical and mechanical infrastructure, the decline of the performance curve is considerably sharper than the structural curve. The STREM line again describes the behaviour of the subway line infrastructure effectively. It is closer to the deterioration curves of electrical and mechanical as expected due to the lifespan difference as explained earlier. Taking into account the fact that the first deterioration curve to pass the performance threshold of 4 out of 10 is the electrical one at the year of 2023, by drawing a vertical line to find where the STREM curve intersects with 2023, a new performance threshold can be designed for the case of this specific subway line. This limit is 6 out of 10 and is shown in the previous figure. In this way, by following the integrated STREM curve of Line 1, the deterioration severity of its electrical parts is not overlooked.

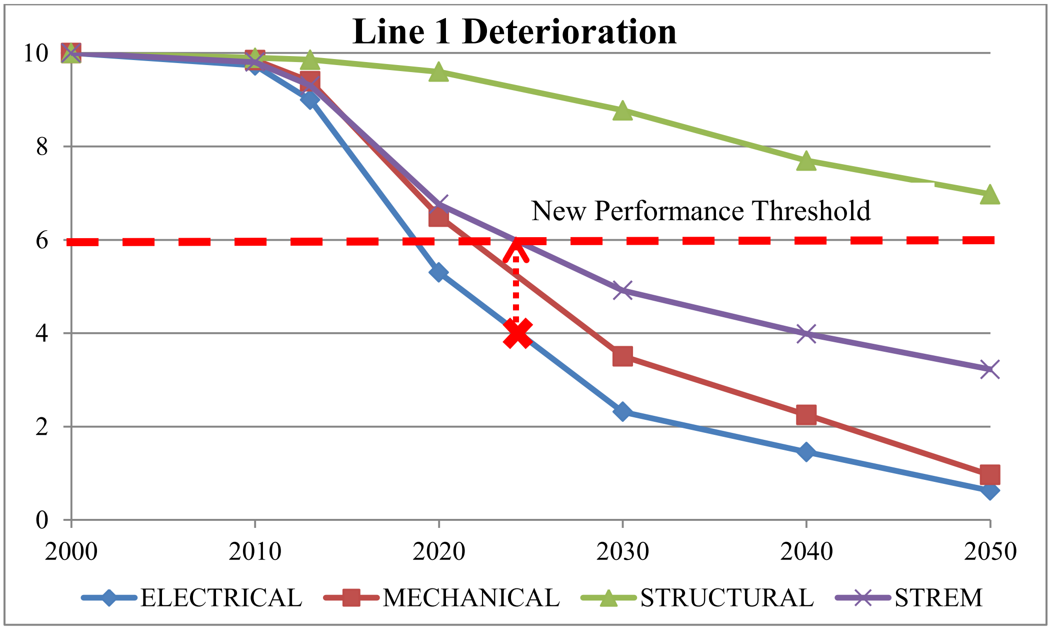


Figure 5.20 Line 1 Deterioration Profile

5.3.8 Subway Network Condition Prediction

The final step of the model implementation to the case study is the deterioration model of the entire studied sub-network. The performance of the network is depending on the performance of its subway lines.

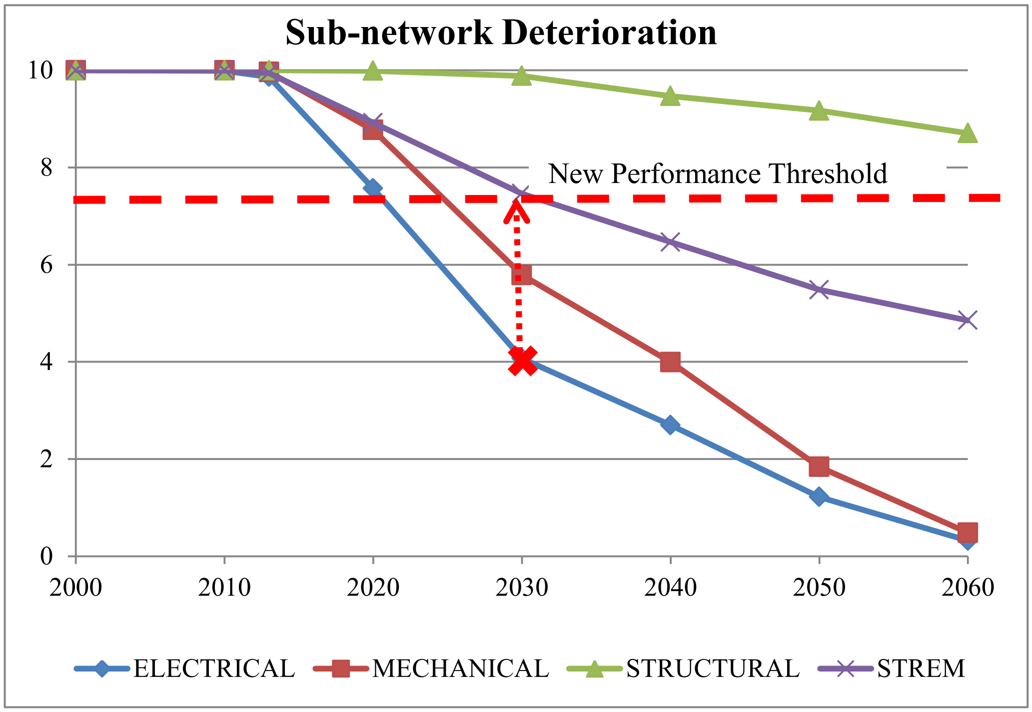


Figure 5.21 Sub-network Deterioration Profile

In Figure 5.21, the deterioration curves of the entire sub-network are illustrated. In the same manner as previously, a new integrated performance threshold can be introduced in the point of STREM ≈ 7/10. In this way, the advanced deterioration of the electrical infrastructure firstly and the mechanical infrastructure secondly is not neglected. The major finding of this graph though is the fact that after 2010 the deterioration begins to accelerate. Overall, the results show that the higher levels of the network such as lines and the network itself record better condition indexes than their respecting stations and components. As explained in the previous sections and in the condition assessment implementation, this is due to the characteristics of the systems reliability theory and mostly due to the absence of tunnels in the calculation process that would cause a reduction in the computed index with the progress of time.

5.4 Model Validation

In order to test the validity of the developed methodology, a comparative study among the results of the case study and results obtained for the same case study from existing researches found in the literature review (Kepaptsoglou et al. 2012, Gkountis and Zayed, 2013) is conducted. The Verification Factor (Zayed and Halpin, 2004) is calculated as a validation measure and the formula to calculate it is illustrated below:

$$VF = \frac{C_{pred}}{C_{act}} = \frac{STREM}{C_{act}} \approx 1 \tag{5.1}$$

Where:

VF = Verification Factor

C_{pred} = Predicted Condition

C_{act} = Actual Condition

In our case, the calculated STREM plays the role of the C_{pred}. As for the C_{act} , the calculated condition indexes from the three referred studies are used. The reason why the integrated condition index (STREM) is selected is because the C_{act} used in the comparison are condition indexes describing the integrated performance of the stations. The VF value should be close to a unit, the closer to 1 it is, the more valid the results are. It should be noted that the comparison is done in the station level, since that is the available information.

In condition indexes from literature are in 0 - 5 scale, so a simple transformation to bring them in 0 - 10 scale is done. In Figure 5.22 the results of the model implementations are plotted and compared with the ones obtained from the literature review.

As it can be seen from Table 5-13, the VF values are close to 1, which is satisfactory. The average Verification Factors for each station is shown in the last column ranging from 0.92 to 1.10.

Table 5-13 Model Verification Factors

	VF DKS	VF MCI	VF ANP	VF avg
Station A_L1	1.13	1.05	1.12	1.10
Station B	0.93	0.92	0.90	0.92
Station A_L2	0.99	1.00	0.97	0.98

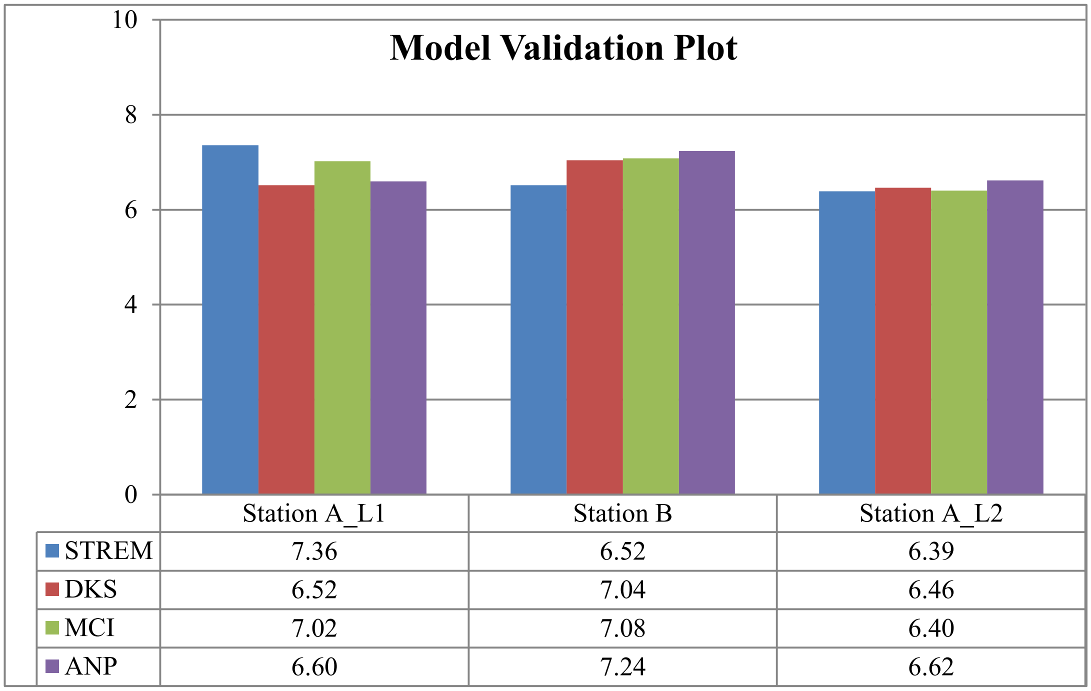


Figure 5.22 Case Study Results Comparison

5.5 Summary

In this chapter the proposed methodology is implemented. At first the relative importance weights of the different components of stations and tunnels are defined along with the weights of their regarding defects. A discussion about the obtained values is done based on the respondents' category. After deriving the final weight values the methodology is applied on a sub-network of Athens. Directly from the station evaluation cards where the components are assigned a score for each of their defects, the component condition assessment process begins resulting in the calculation of the component condition index. With the CIs of the components known, the following step is the evaluation of the station condition index for each type of infrastructure namely, electrical, mechanical and integrated with structural (STREM). From the stations level and continuing upwards in the hierarchy, the subway line condition and eventually the entire subway network's performance is evaluated. The case study continues with the condition prediction model. Component deterioration curves are constructed and based on them and the future conditions of the components, the deterioration profile of stations is designed. That enables the drawing of deterioration curves for the remaining hierarchy levels, namely the line and the network deterioration profile. Again the performance curves can be relevant to each separate type of infrastructure (electrical, mechanical etc.) or integrated (STREM). From these graphs, performance thresholds can be adopted. Finally, the results of the model implementation are compared with findings from the literature for the same case study and the methodology is validated through the computation of the verification factor.

6 STREM Automated Tool

6.1 Introduction

The use and application of all the discussed and analyzed techniques should not be an obstacle of transit authorities or any other interested stakeholders. Living in the era of automation, where everything has to be carried out fast and effectively, the entire developed methodology is incorporated in a user-friendly automated platform. The developed software is called "STREM Automated Tool" (STRuctural/ Electrical/ Mechanical). The main calculation volume is done on Excel sheets and the interface is developed with Matlab. The input of data is done directly on the interface and the results are presented there and also are stored in Excel sheets. The developed software can support a network of maximum 3 lines and 6 stations and tunnels in each line. That is one limitation of the software, but again the development of an advanced and comprehensive commercial software is outside the scope of this research. In Figure 6.1 the flowchart of the software is illustrated.

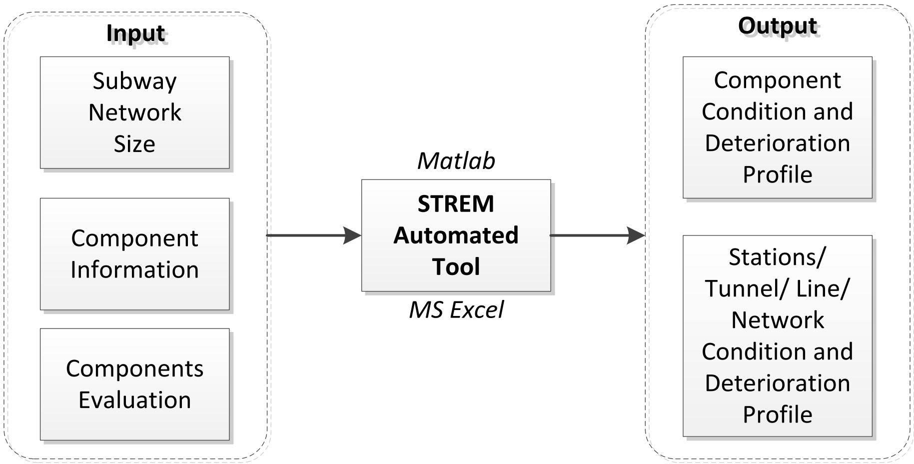
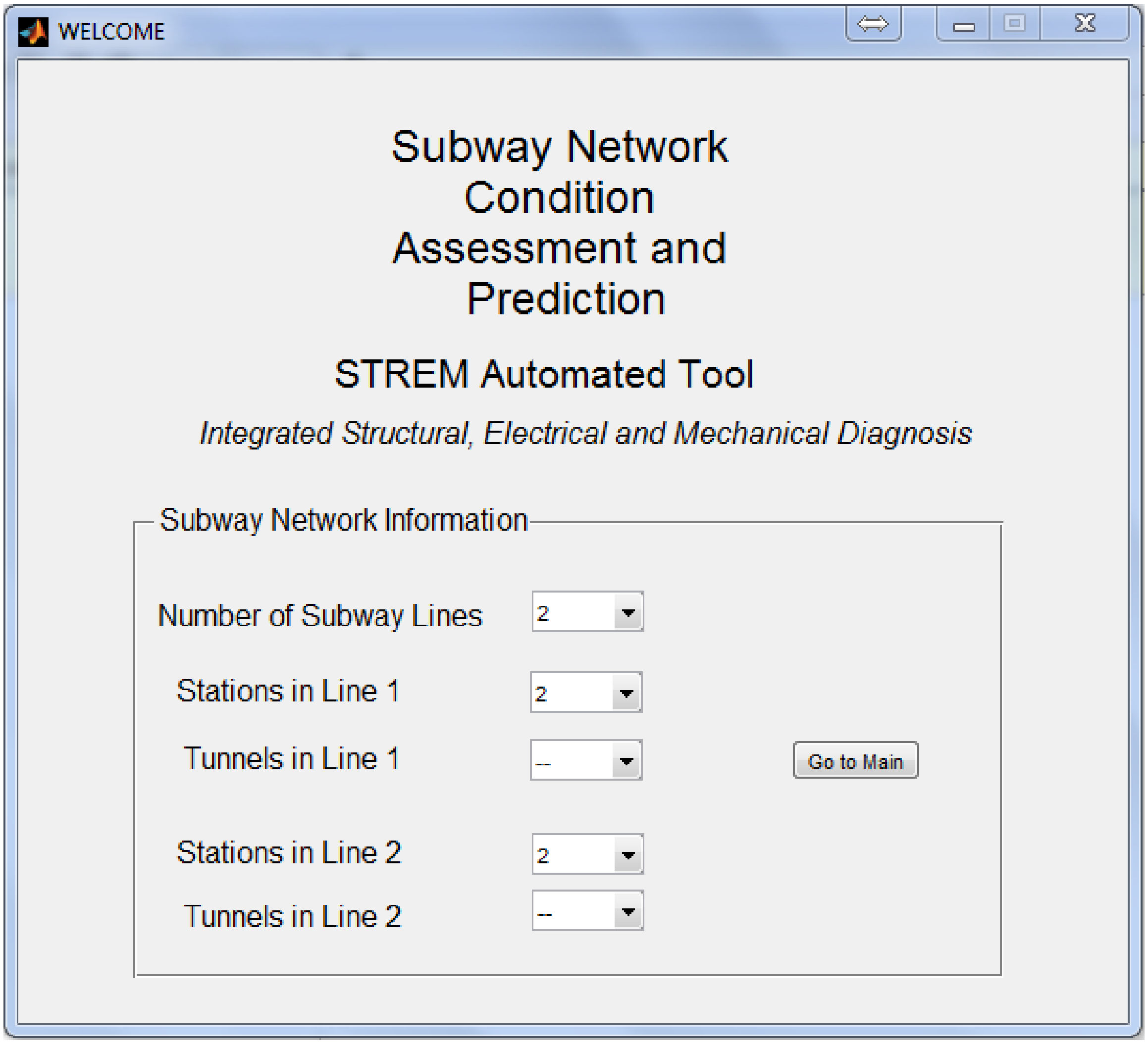


Figure 6.1 STREM Automated Tool Diagram

6.2 STREM Automated Tool Interface

By clicking on the “main” Matlab file the software begins to work. The first window that appears is the “Welcome” window where the user can define the size of the network by selecting the number of subway lines and number of stations and tunnels in each line. A snapshot of the “Welcome” window is seen in Figure 6.2



Subway Network Condition Assessment and Prediction

STREM Automated Tool

Integrated Structural, Electrical and Mechanical Diagnosis

Subway Network Information

Number of Subway Lines 2

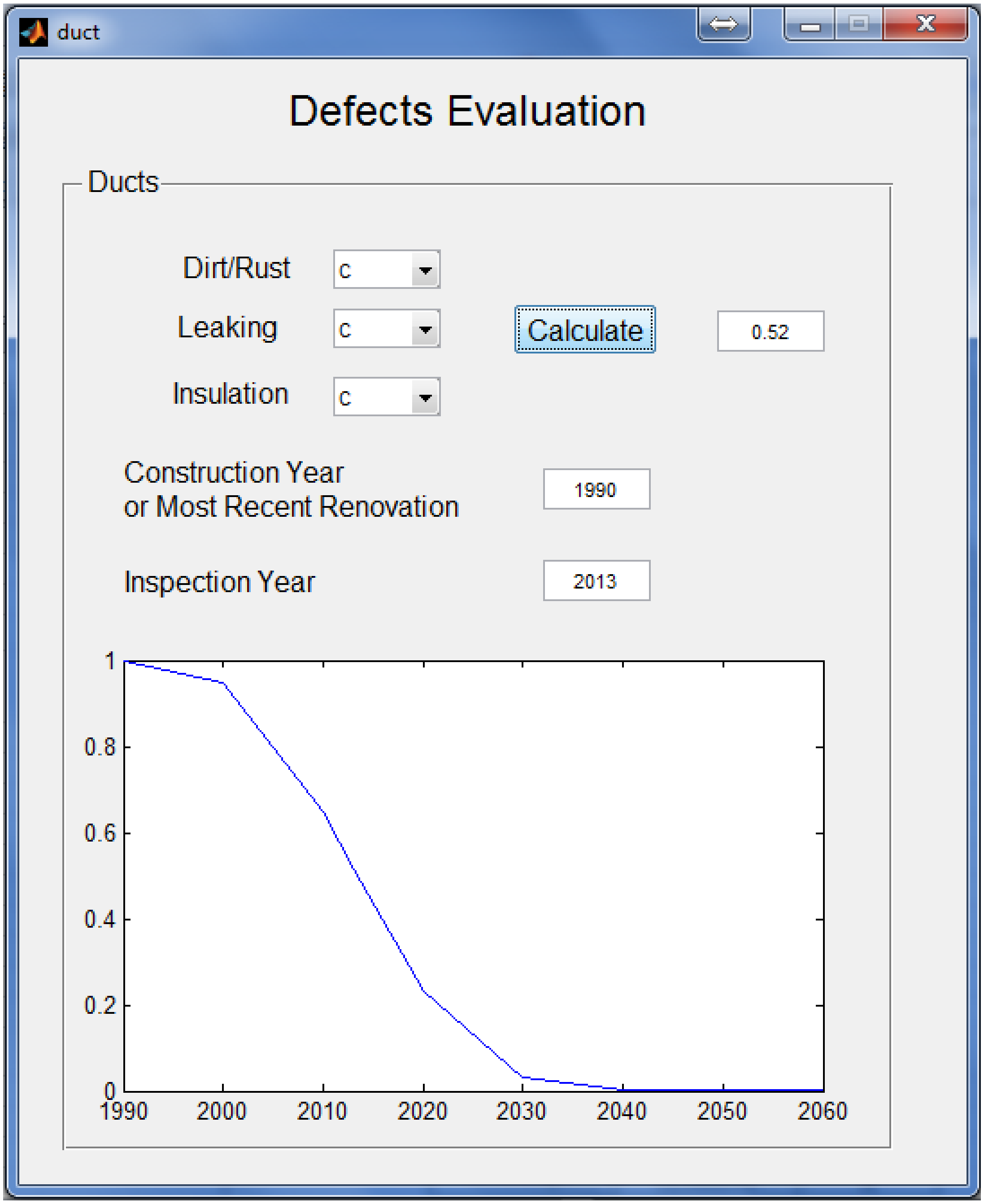
Stations in Line 1 2

Tunnels in Line 1 --

Stations in Line 2 2

Tunnels in Line 2 --

Figure 6.2 STREM Automated Tool "Welcome" Screen



Defects Evaluation

Ducts

Dirt/Rust: c

Leaking: c

Insulation: c

0.52

Construction Year or Most Recent Renovation: 1990

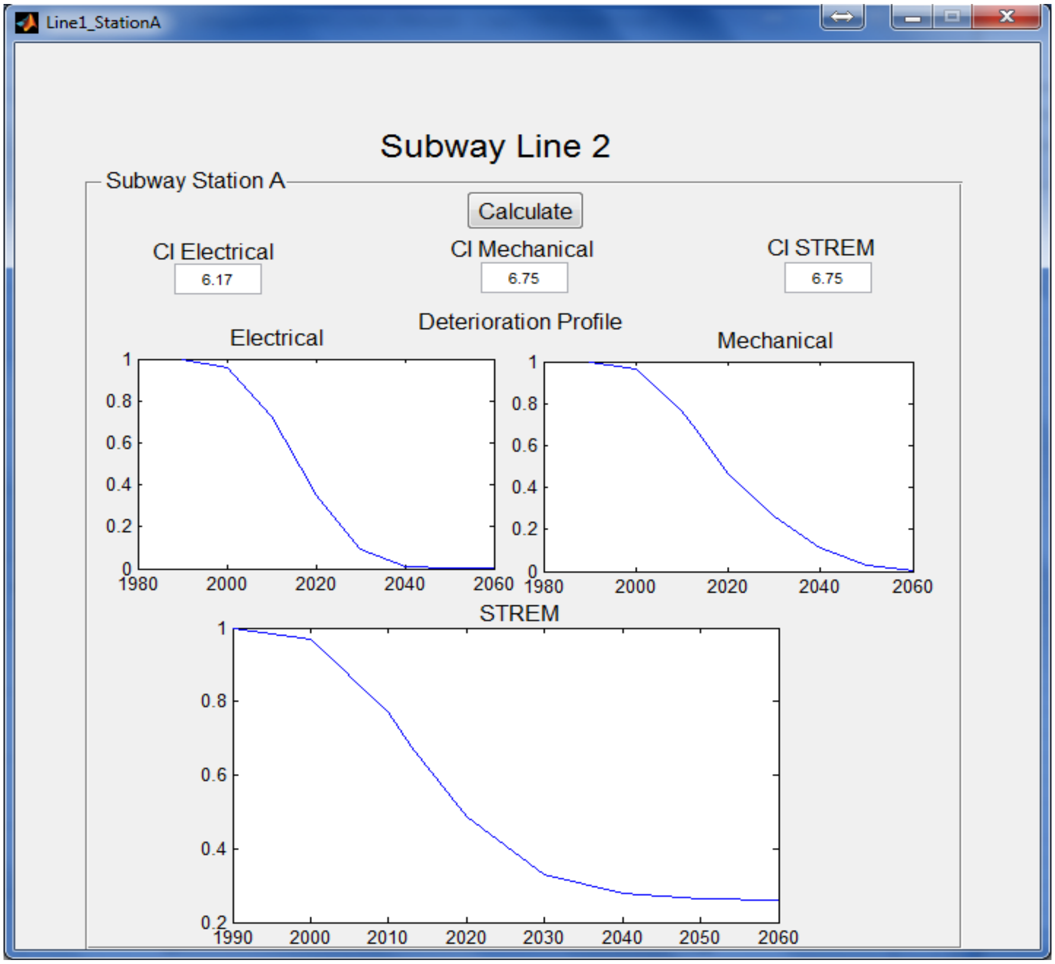
Inspection Year: 2013

Figure 6.3 STREM Automated Tool Component Window

After inputting the network characteristics, then the condition assessment and condition prediction processes initiate. Repetitive windows pop up where the user selects the relative defect rating from the drop-list of each component. Every window includes only one component. In addition, users are asked to enter the construction year and the inspection year in order to find the age of the component. After finishing the data input process, the user can click on the “Calculate” button. The program performs all the necessary calculation in the background and the component condition index is shown in the relative box. Finally, with the component condition index known, more calculations take place in the background and the component deterioration curve is drawn on the diagram space of the window. A typical “Component” window is provided in

The same process is repeated for all the components of every examined station and tunnel included in the examined network. After finishing the component evaluation process, the “Station” windows continue. At that point, the user is facing one window for each of the examined stations. There is no need for further input at this stage since all necessary information come from the input at the component level. A simple click on the “Calculate” button initiates the computation process. The electrical, mechanical and STREM indexes are calculated and shown in the respecting boxes. In addition the software draws the deterioration curves for each type of infrastructure (electrical, mechanical and integrated) for this specific station as in Figure 6.4.

A similar window arises for all the examined stations and tunnels. After finishing this step, a window relative to the subway line shows up. Similar as before, after clicking on the “Calculate” button the electrical, mechanical and STREM indexes of the subway line are constructed. A typical Line window is demonstrated in Figure 6.5.



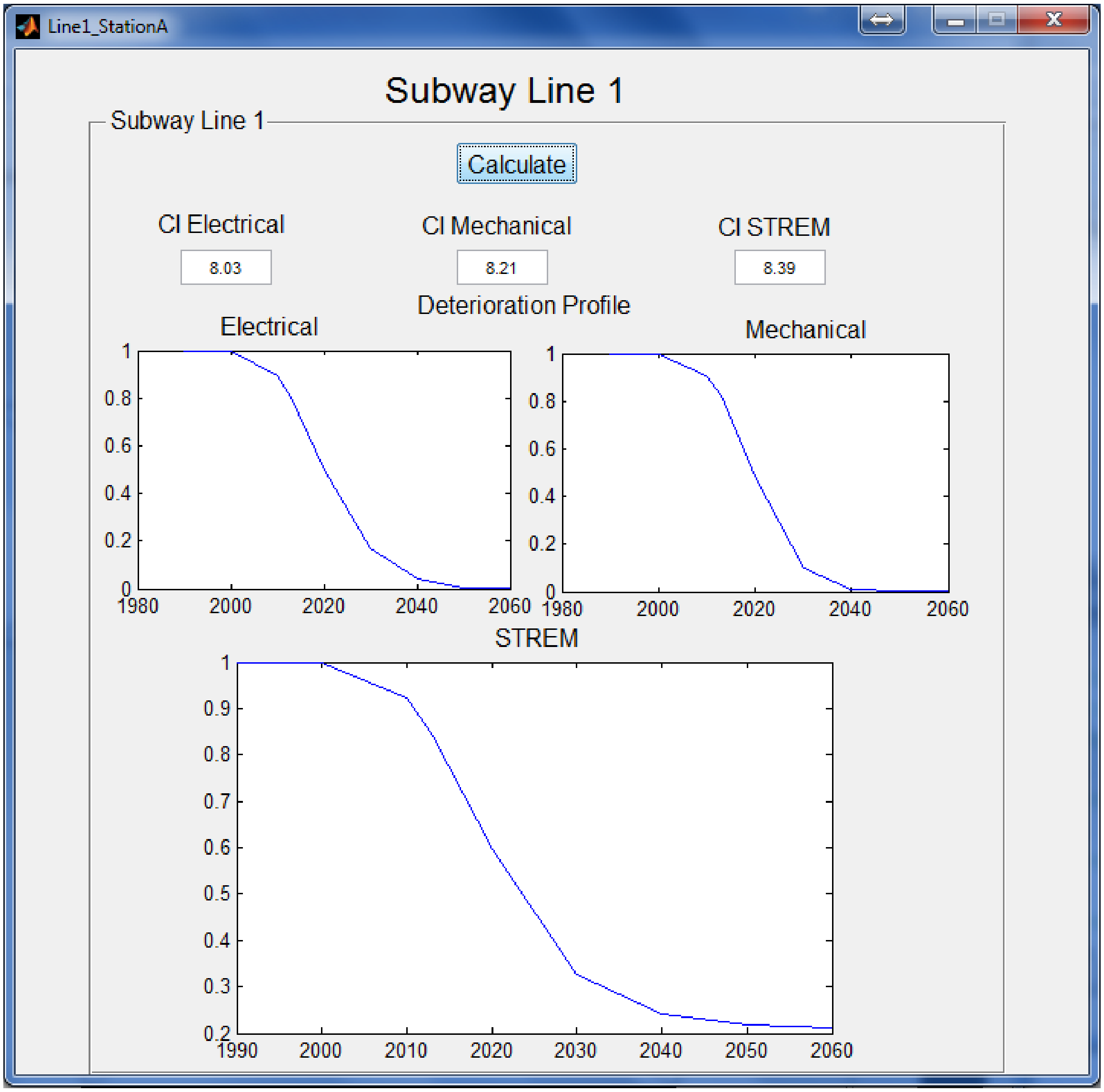
CI Electrical 6.17

CI Mechanical 6.75

CI STREM 6.75

Figure 6.4 STREM Automated Tool Station Window

The last step of the program is concerning the condition evaluation of the entire network. This is also the last window of the software. In the same pattern as for stations, tunnels and lines, all the necessary information have been retrieved already from the previous windows and with the click of the “Calculate” button, the electrical, mechanical and STREM condition indexes are calculated and presented. A background process finally provides the deterioration curves of the network as seen in Figure 6.6



CI Electrical 8.03

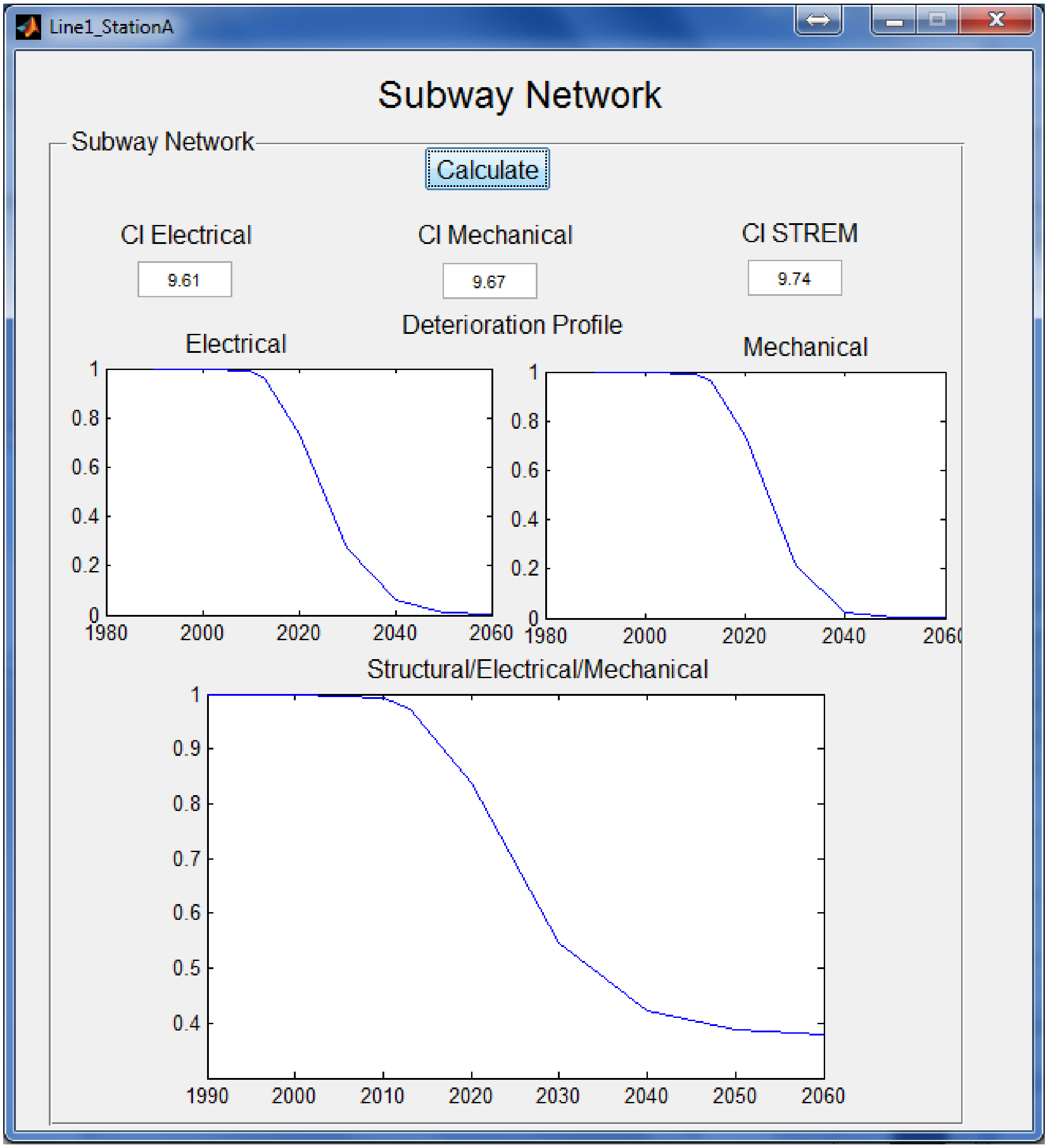
CI Mechanical 8.21

CI STREM 8.39

Figure 6.5 STREM Automated Tool Line Window

6.3 Summary

The STREM Automated Tool is presented in this chapter. The developed software is incorporating the suggested methodology in a user-friendly interface that facilitates its use by transit authorities and other interested parties without having to undergo the complex mathematical calculation process. The input for the software is the size of the network and the defects evaluation of each component. The output is the condition indexes for all levels of the subway network hierarchy (components, stations/ tunnels, lines, network) and the relevant deterioration curves. The data input process is straightforward and the results computation is fast.



CI Electrical 9.61

CI Mechanical 9.67

CI STREM 9.74

Figure 6.6 STREM Automated Tool Network Window

7 Conclusions and Recommendations

7.1 Summary

Subway networks are the most essential means of transportation for passengers in large metropolitan areas. Infrastructure is nowadays facing extensive deterioration due to aging while there is an increasing demand for transportation. Transit authorities are under pressure to develop asset management tools to achieve better level of service and manage capital more efficiently. In this context, this research is proposing a new condition assessment and prediction model for subway networks.

A subway infrastructure component breakdown is proposed and the condition assessment process begins in the component level, where the evaluation is done based on actual defects resulting in the calculation of the component condition index. Defect weights are calculated with the AHP, scores are transformed with the Fuzzy Canonical Operation and the aggregation is performed with TOPSIS. The station and tunnel condition is then evaluated based on the respective components rating. At this point, electrical and mechanical condition indexes are calculated and the integration with current structural performance evaluation models is suggested. Component weights are determined with the use of ANP and TOPSIS is used for the combination of scores and weights to form the integrated structural, electrical and mechanical condition index, called STREM. Then a formula for the calculation of the condition of the upper levels of the subway network hierarchy (subway lines and network) is provided adopting a reliability-based approach. The methodology continues with the development of a condition prediction model, which is done in the component level based on Weibull theory and results in the construction of component deterioration curves. The relevant deterioration profiles of stations, tunnels, subway lines and the entire network are then designed with the implementation of the condition assessment process for the future component states as they can be extracted from the respective component deterioration curves.

7.2 Conclusions

Several conclusions can be drawn from the development and implementation of the condition assessment and prediction model.

- Overheating turns out to be the most important defect of electrical components, recording a weight of 46% and 66% for lightning and emergency lightning, whereas service interruption is the most crucial defect of distribution cables and panels with weights of 51% and 46% respectively.
- Pipes are mostly affected by cracking (49%), boilers by leaking (35%) and overheating (33%). The most considerable defect of air handling units is the presence of dirt/mold/rust with a weight of 65%. Flooding (45%) is the most essential defect of track drainage and mechanical damage (76%) for escalators.
- Emergency Lightning is the component contributing the most to the station's electrical infrastructure with a weight of 31.4%. Escalators (29%) record the highest weight of the mechanical infrastructure of stations, followed by elevators (20%) and fire extinguish (14%).

- In the case of subway tunnels' electrical infrastructure, emergency lightning possesses an importance of 42%.
- As far as the tunnels mechanical components are concerned, ducts (39%) are the most dominant component followed by fire extinguish (28%).
- The final obtained weights included in the model implementation are closer to those calculated from the responses received by experts with subway-related experience and to the weights originating from respondents in the managerial level.
- From the model implementation to the case study, there are no observed components with an immediate need for intervention actions. The lowest recorded condition index was 5.167, measured in few components, such as ducts and air handling units of Station A in Line 1 and Station B in Line 2, and emergency lightning in Station A in Line 2 and Station B of Line 1. The remaining components are scoring an index of 7.167 and 9.167.
- Subway stations are in good condition with STREM score ranging from 6.95 – 7.36, with Station A in Line 1 being the best. In general structural infrastructure is found to be in better shape, followed by the mechanical and electrical infrastructure as can be seen from the isolated infrastructure type condition indexes.
- Both examined subway lines perform excellent scoring condition indexes, around 9, as is the case for the entire network.

- , Setting the acceptable performance threshold to 4 out of 10 for the condition prediction model, it was found that some components should be planned for maintenance or renovation activities between 2015 and 2020.
- Stations' integrated (STREM) deterioration curves can effectively describe the deterioration of the different types of infrastructures and show repair need around 2020.
- In the case of subway lines, a new performance threshold can be introduced to STREM index 6 out of 10 as imposed by the faster deterioration of the electrical infrastructure and in 7 out of 10 for the network.
- The calculated STREM indexes do not vary significantly from actual condition indexes for the same case study recording acceptable Verification Factor values ranging from 0.92 to 1.10, which is sufficiently close to 1.

7.3 Research Contributions

The developed methodology provides a new condition assessment and deterioration prediction model for subway networks. The most significant contributions of this research are listed as follows:

- A subway network hierarchy of components is proposed including electrical and mechanical infrastructure.
- A customized version of TOPSIS with fixed upper and lower limits and stepwise implementation is provided thus rendering the technique to be applicable in a wider range of decision problems whose target is the calculation of an index as the selection measurement.

- Introduces a defect-based condition rating method of subway electrical and mechanical components.
- It provides electrical, mechanical and integrated (STREM) condition indexes and deterioration curves for stations/tunnels, subway lines and network and introduces performance thresholds for each subway network level.
- The “STREM Automated Tool” is offered facilitating the fast and user-friendly implementation of the developed models from the interested users, such as transit authorities, infrastructure asset managers, subway practitioners and researchers.

7.4 Research Limitations

The developed methodology possesses some weaknesses as seen in the following list:

- It is structured on a firm scheme of subway components for which relative importance weights are calculated. If additional components are introduced, new weights have to be computed from the ANP process.
- Similarly, component condition is evaluated based on a proposed hierarchy of defects. In the scenario of a need for new or different defects, a new AHP-based weight calculation process has to be performed.
- The developed model is implemented on a sub-network and is validated through the comparison of calculated station condition indexes with results for the same case study from other models. A validation of tunnels, lines and network performance is also needed.
- The “STREM Automated Tool” is not dynamic; it uses the calculated weights and does not allow users to modify them based on their preference or judgment.

7.5 Recommendations and Future Work

The developed methodology accomplished the objectives of this research. A performance assessment and deterioration model was established, applied on a case study and was validated. Still, there is room for improvement in the methodology characteristics and extension of the research scope. Some recommendations and future work proposals are listed below:

- Additional components and elements can be introduced to the model, such as light bulbs, circuit breakers, plumbing fixtures, pumps, fare collectors, signaling and control systems, emergency generators, fiber optic and telecom cables, CCTV system etc. further decomposing subway networks for a better representation of the factors contributing to the global condition of the system.
- In a similar manner, a wider, more inclusive list of defects can be identified and considered in the condition assessment process.
- Technology-based defect evaluation can be incorporated to the model so as defects scores will be directly linked with relevant equipment measurements, such as auto-leak detection and air quality sensors, infrared electrical inspection, vibrators etc. to completely eliminate visual inspection uncertainty, subjectivity and inaccuracy.
- The calculated relative importance weights were derived from the information gathered by 23 experts. The on-line survey can be forwarded to a larger audience and thus, obtain more reliable weights.
- The "STREM Automated Tool" can be adapted to a web version, simplifying its accessibility to interested parties.

- The developed methodology can be implemented in more subway networks to explore its potential capacities and check the validity of results. In addition, the model's strength of comparing networks through a unified system/scale (CI, STREM) can be examined after application to different networks.
- The outcomes of this research can also be included in the structure of risk assessment models assuming that the probability of system failure is the adverse of the current condition (one minus current).
- Moreover, maintenance, repair and rehabilitation planning features can be built upon the results of this model, as well as life cycle cost models can be supplementary to these models, eventually forming a complete subway asset management tool.
- The developed methodology can be modified in order to be applicable in other types of infrastructure with similar characteristics such as highway and road networks, bridges and pipeline networks.
- The results of customer satisfaction surveys regarding the infrastructure and serviceability of subways could be added to this research in order to form an integrated engineering-managerial-client based approach.

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APPENDIX I Defect Weights by Expert Group

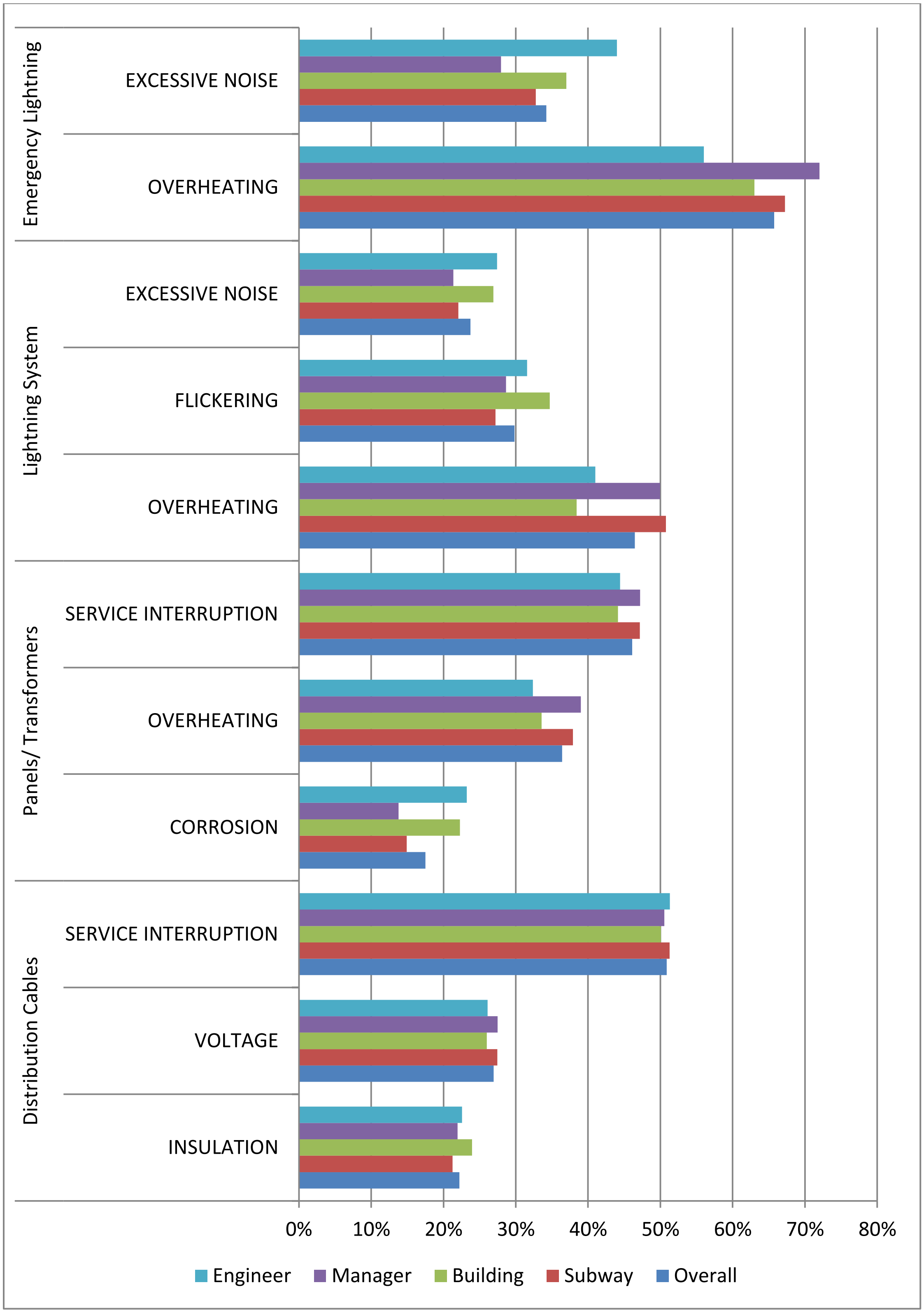
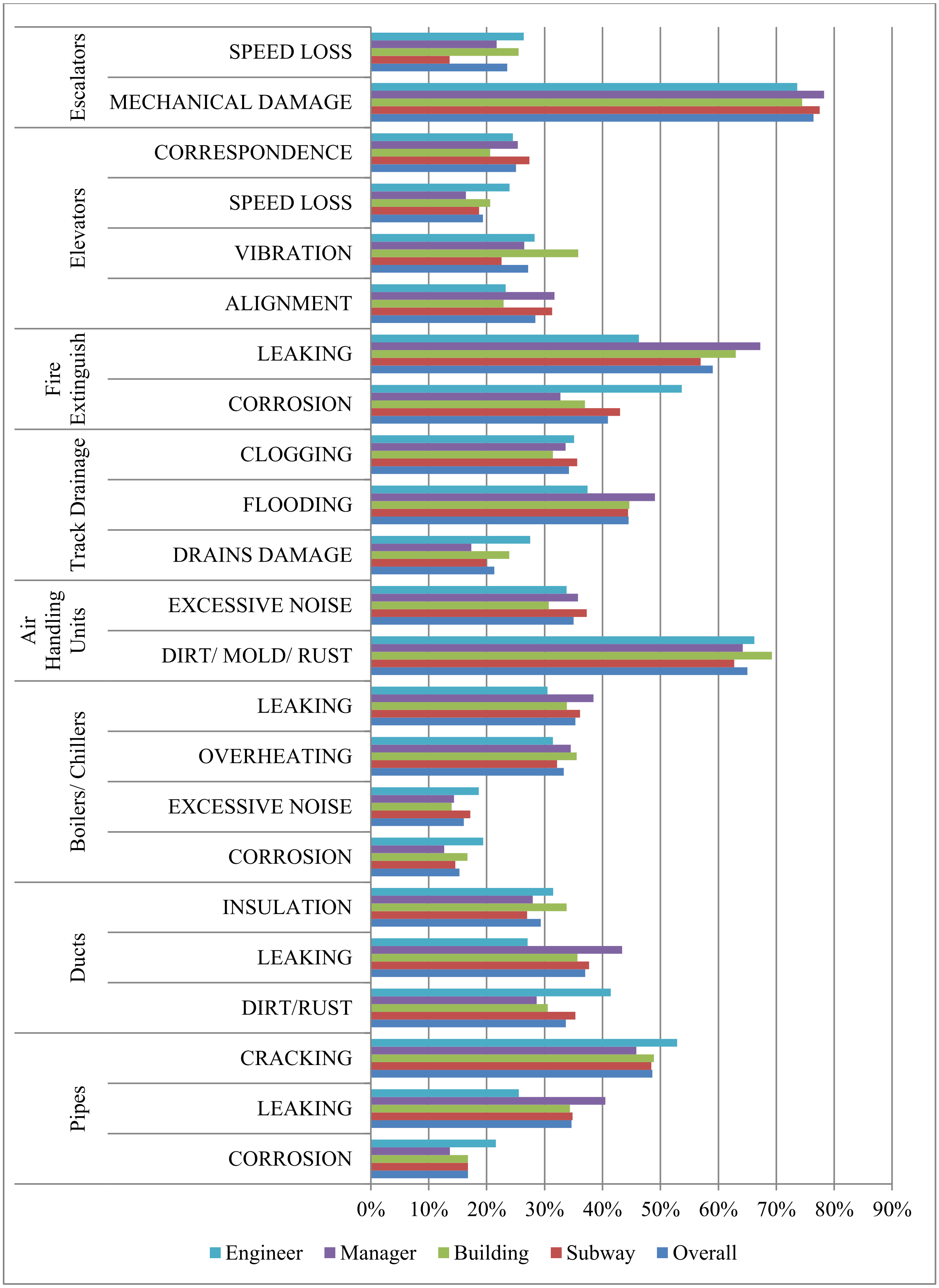


Figure A.1 Electrical Defect Weights by Expert Group



FigureA.2 Mechanical Defect Weight by Expert Group

Table A-1 Electrical Defects Difference by Expert Group

Component	Defect	Difference subway	Difference building	Difference manager	Difference engineer
Distribution Cables	INSULATION	4%	-8%	1%	-2%
	VOLTAGE	-2%	4%	-2%	3%
	SERVICE INTERRUPTION	-1%	2%	1%	-1%
Panels/ Transformers	CORROSION	15%	-27%	21%	-33%
	OVERHEATING	-4%	8%	-7%	11%
	SERVICE INTERRUPTION	-2%	4%	-2%	4%
Lightning System	OVERHEATING	-9%	17%	-8%	12%
	FLICKERING	9%	-16%	4%	-6%
	EXCESSIVE NOISE	7%	-13%	10%	-16%
Emergency Lightning	OVERHEATING	-2%	4%	-10%	15%
	EXCESSIVE NOISE	4%	-8%	18%	-28%

Table A-2 Mechanical Defects Difference by Expert Group

Component	Defect	Difference overall-subway	Difference building	Difference manager	Difference engineer
Pipes	CORROSION	0%	0%	18%	-29%
	LEAKING	0%	1%	-17%	26%
	CRACKING	0%	-1%	6%	-9%
Ducts	DIRT/RUST	-5%	9%	15%	-23%
	LEAKING	-2%	4%	-17%	27%
	INSULATION	8%	-15%	5%	-7%
Boilers/ Chillers	CORROSION	5%	-9%	17%	-27%
	EXCESSIVE NOISE	-7%	13%	10%	-16%
	OVERHEATING	4%	-7%	-4%	6%
	LEAKING	-2%	4%	-9%	14%
Air Handling Units	DIRT/ MOLD/ RUST	4%	-7%	1%	-2%
	EXCESSIVE NOISE	-7%	12%	-2%	3%
Track Drainage	DRAINS DAMAGE	7%	-12%	19%	-29%
	FLOODING	0%	0%	-10%	16%
	CLOGGING	-4%	8%	2%	-3%
Fire Extinguish	CORROSION	-5%	10%	20%	-31%
	LEAKING	4%	-7%	-14%	22%
Elevators	ALIGNMENT	-10%	19%	-12%	18%
	VIBRATION	17%	-32%	3%	-4%
	SPEED LOSS	3%	-6%	15%	-24%
	CORRESPONDENCE	-9%	18%	-1%	2%
Escalators	MECHANICAL DAMAGE	-1%	3%	-2%	4%
	SPEED LOSS	42%	-8%	8%	-12%

APPENDIX II Case Study Deterioration Curves

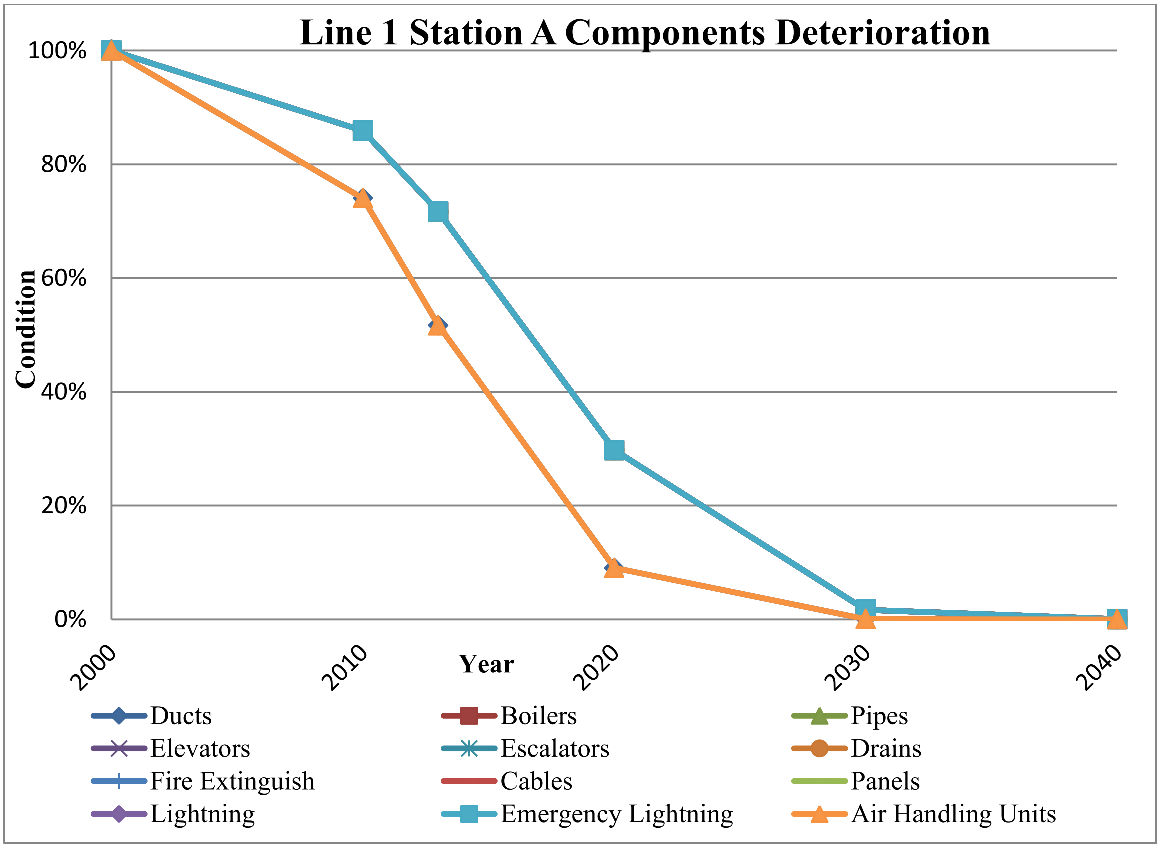
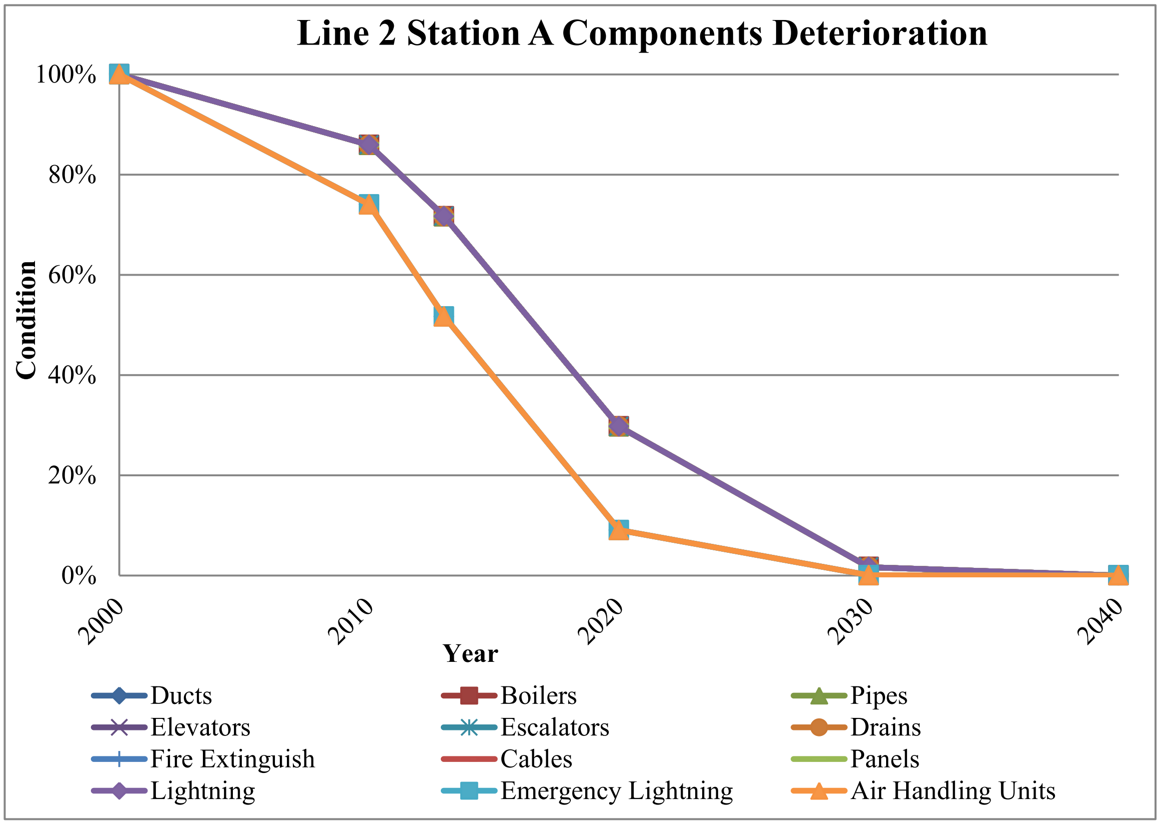
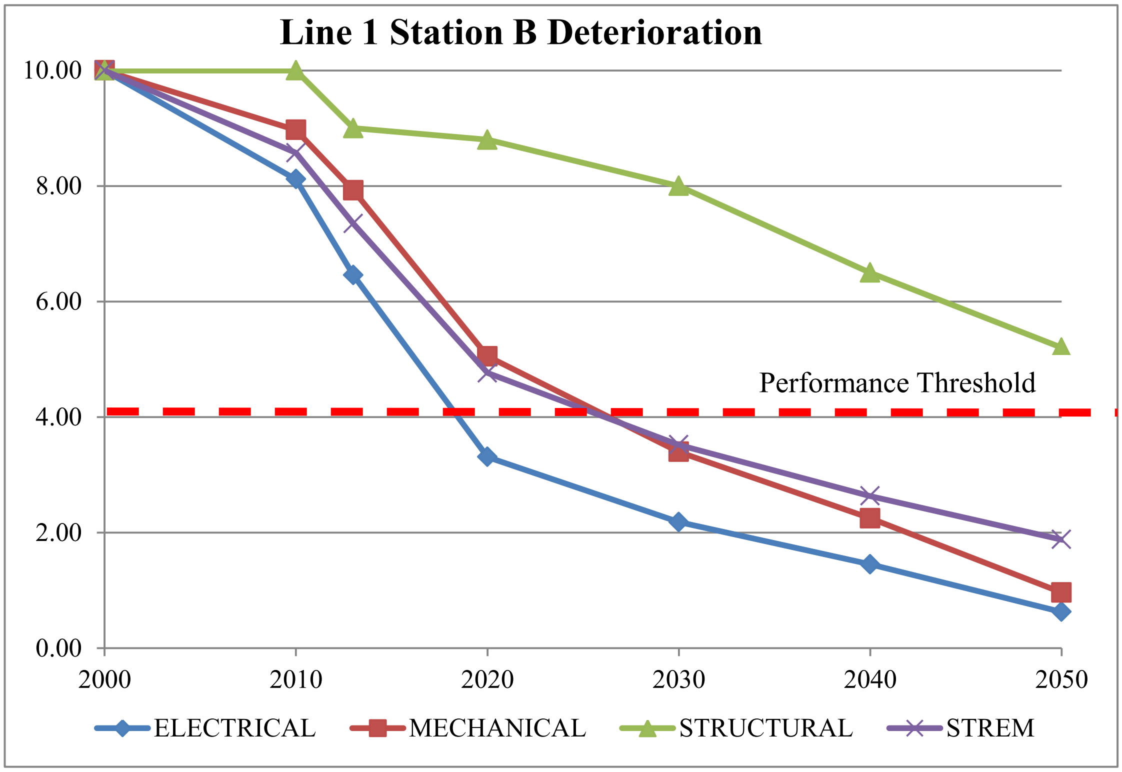


Figure A.3 Line 1 Station A Components Deterioration Curves



FigureA.4 Line 2 Station A Components Deterioration



FigureA.5 Line 1 Station B Deterioration

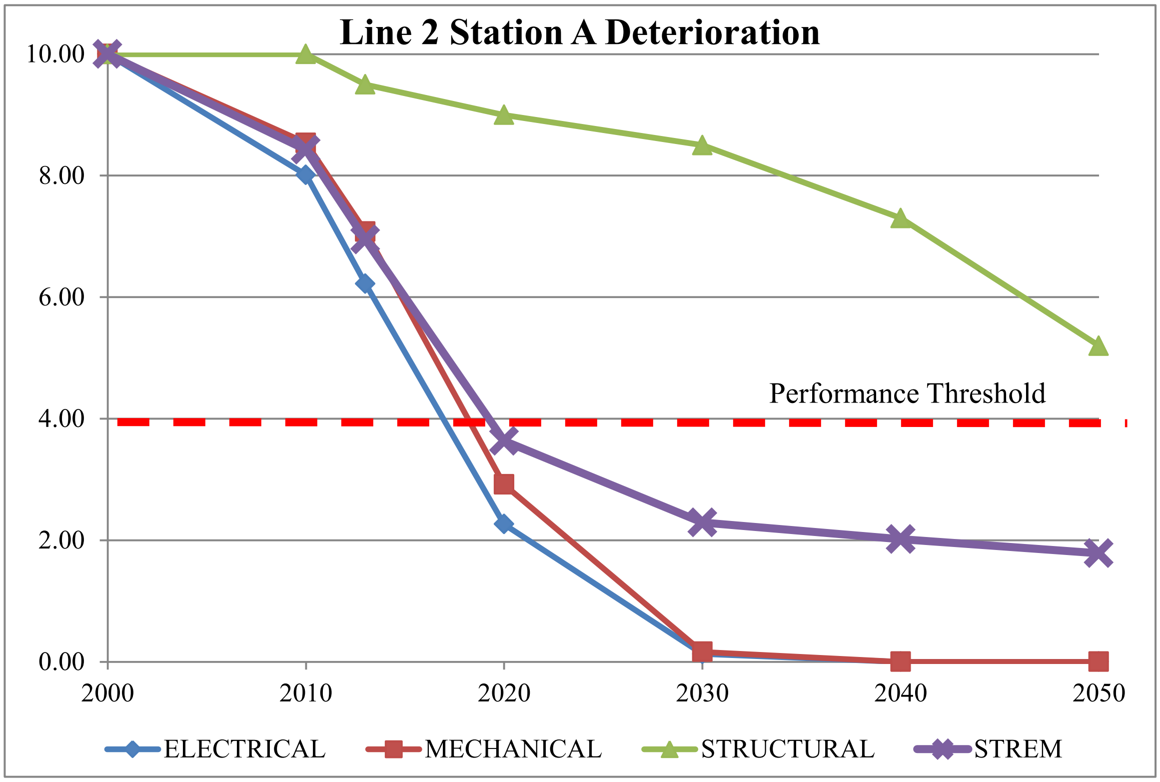


Figure A.6 Line 2 Station A Deterioration

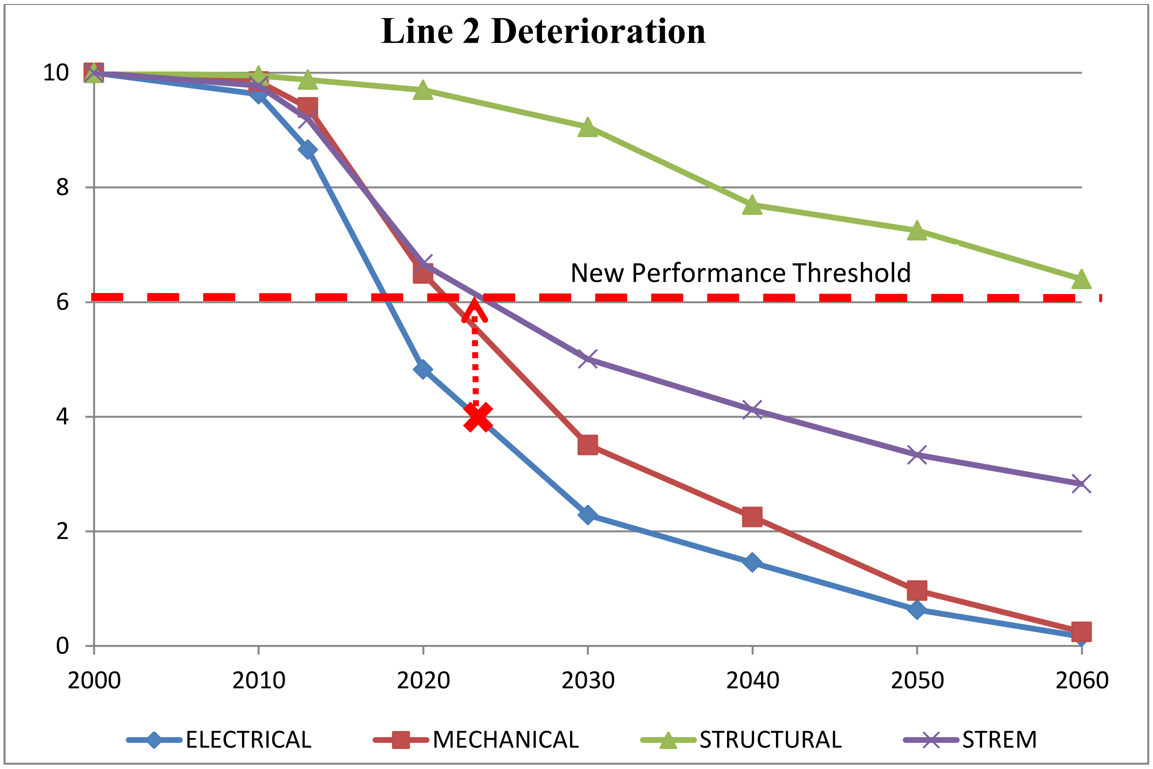


Figure A.7 Subway Line 2 Deterioration

APPENDIX III Analytic Network Process Samples

Table A-3 ANP Unweighted Matrix Station Components

	Cabl	Emerg	Light	pan	AirH	Boil	Ducts	HVAC	MSyst	MEqpm	Elev	Esc	FXt	Pip	Drain	Slabs	Stairs	Walls	ELECl	MECH	STR	STAT
Cabl	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.11688	0	0	0
Emerg	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.49351	0	0	0
Light	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.3896	0	0	0
pan	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.35065	0	0	0
AirH	0	0	0	0	0	0	0	0.33333	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Boil	0	0	0	0	0	0	0	0.33333	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Ducts	0	0	0	0	0	0	0	0.33333	0	0	0	0	0	0	0	0	0	0	0	0	0	0
HVAC	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0.0667	0	0
MSyst	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0.4667	0	0
MEqpm	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0.4667	0	0
Elev	0	0	0	0	0	0	0	0	0.75	0	0	0	0	0	0	0	0	0	0	0	0	0
Esc	0	0	0	0	0	0	0	0	0.25	0	0	0	0	0	0	0	0	0	0	0	0	0
FXt	0	0	0	0	0	0	0	0	0	0.42857	0	0	0	0	0	0	0	0	0	0	0	0
Pip	0	0	0	0	0	0	0	0	0	0.42857	0	0	0	0	0	0	0	0	0	0	0	0
Drain	0	0	0	0	0	0	0	0	0	0.14286	0	0	0	0	0	0	0	0	0	0	0	0
Slabs	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.33333	0
Stairs	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.33333	0
Walls	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.33333	0
ELECl	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.75	0.75	0.6
MECH	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.75		0.25	0.2
STR	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.25	0.25	0	0.2
STAT	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table A-4 ANP Limiting Matrix Sttaion Components

	Cabl	Emerg	Light	pan	AirH	Boil	Ducts	HVAC	MSyst	MEqpm	Elev	Esc	FXt	Pip	Drain	Slabs	Stairs	Walls	ELECl	MECH	STR	STAT
Cabl	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.018262	0.018262	0.018262	0.018262
Emerg	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.077111	0.077111	0.077111	0.077111
Light	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.006088	0.006088	0.006088	0.006088
pan	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.054789	0.054789	0.054789	0.054789
AirH	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.006019	0.006019	0.006019	0.006019
Boil	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.006019	0.006019	0.006019	0.006019
Ducts	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.006019	0.006019	0.006019	0.006019
HVAC	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.009028	0.009028	0.009028	0.009028
MSyst	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.063194	0.063194	0.063194	0.063194
MEqpm	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.063194	0.063194	0.063194	0.063194
Elev	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.094792	0.094792	0.094792	0.094792
Esc	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.031597	0.031597	0.031597	0.031597
FXt	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.054166	0.054166	0.054166	0.054166
Pip	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.054166	0.054166	0.054166	0.054166
Drain	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.018055	0.018055	0.018055	0.018055
Slabs	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.024306	0.024306	0.024306	0.024306
Stairs	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.024306	0.024306	0.024306	0.024306
Walls	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.024306	0.024306	0.024306	0.024306
ELECl	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.15625	0.15625	0.15625	0.15625
MECH	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.135417	0.135417	0.135417	0.135417
STR	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.072917	0.072917	0.072917	0.072917
STAT	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

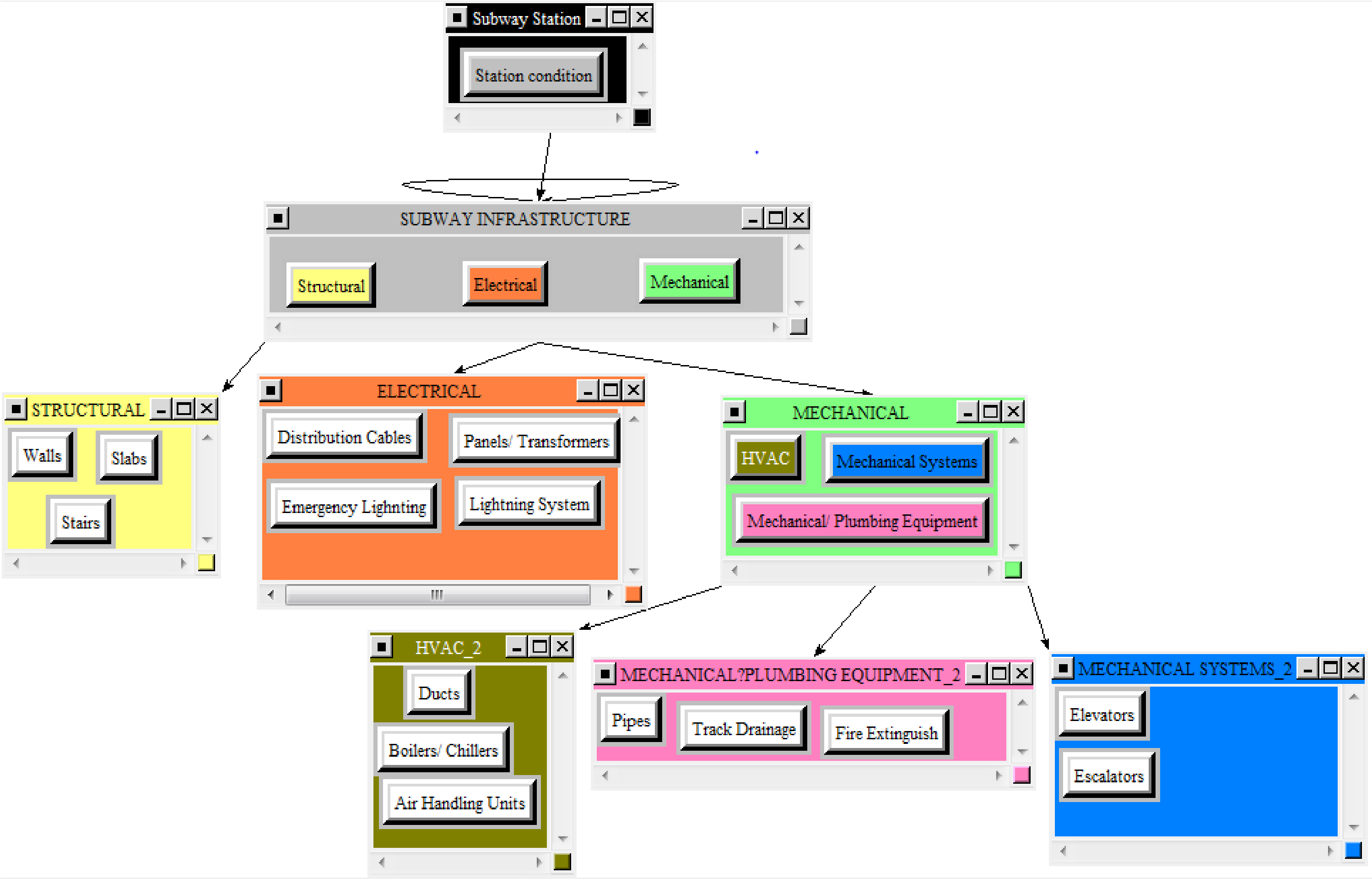
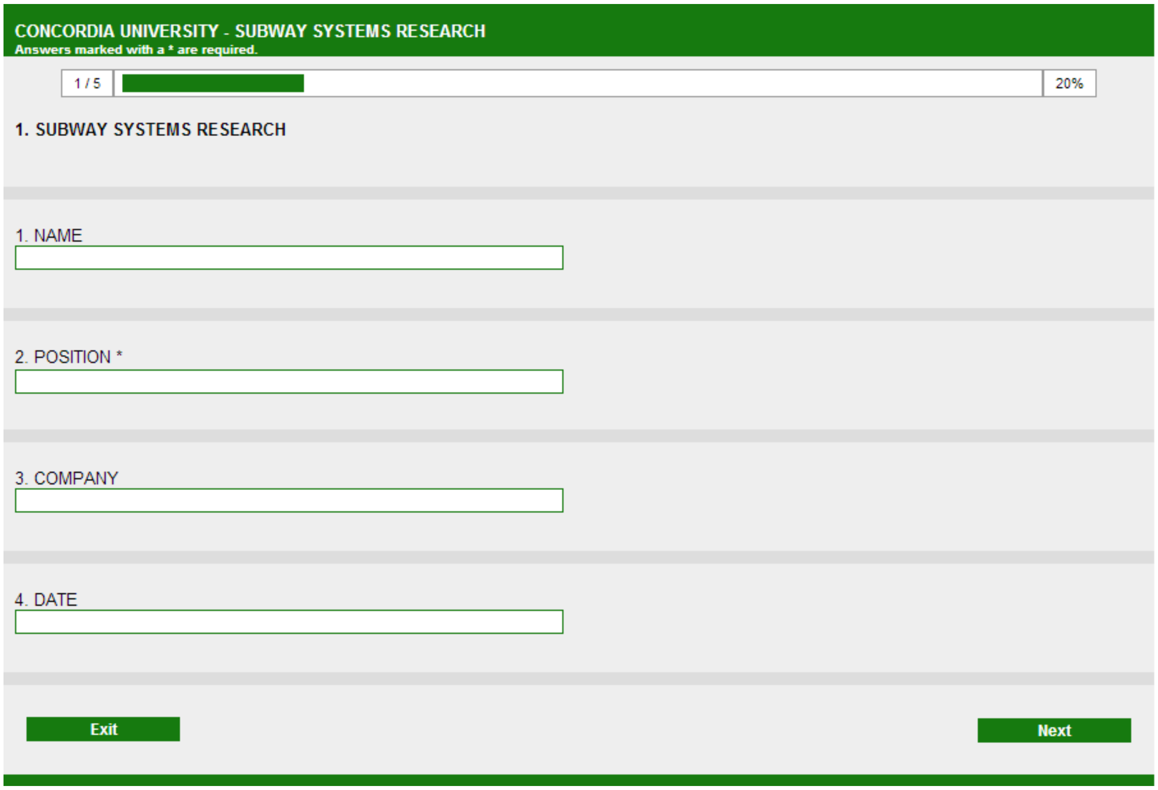


Figure A.8 ANP Super Decisions Station Network

APPENDIX IV ON-LINE SURVEY



CONCORDIA UNIVERSITY - SUBWAY SYSTEMS RESEARCH

Answers marked with a * are required.

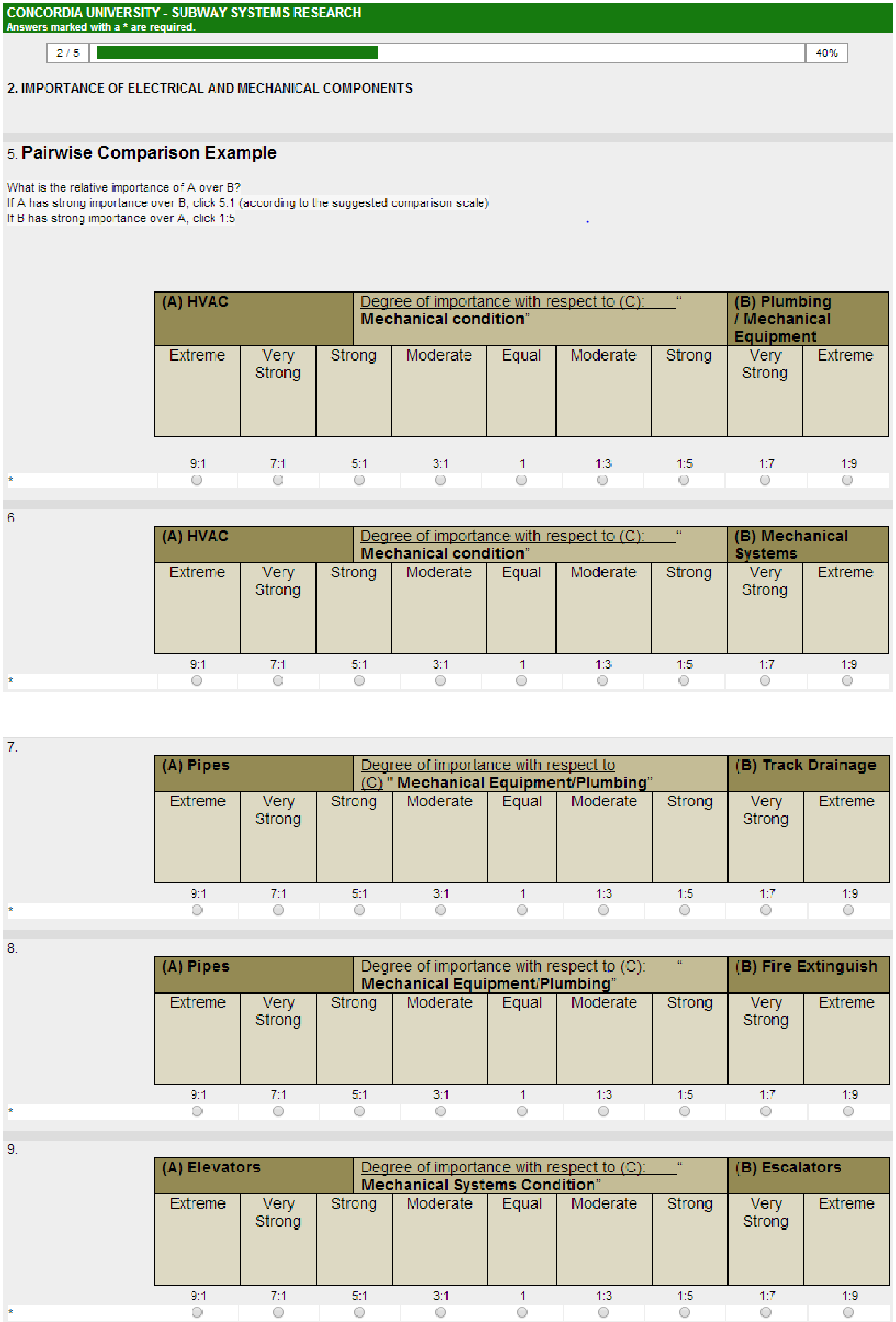
1. SUBWAY SYSTEMS RESEARCH

1. NAME

2. POSITION *

3. COMPANY

4. DATE



CONCORDIA UNIVERSITY - SUBWAY SYSTEMS RESEARCH
Answers marked with a * are required.

2 / 5 | 40%

2. IMPORTANCE OF ELECTRICAL AND MECHANICAL COMPONENTS

5. **Pairwise Comparison Example**

What is the relative importance of A over B?
If A has strong importance over B, click 5:1 (according to the suggested comparison scale)
If B has strong importance over A, click 1:5

	(A) HVAC		Degree of importance with respect to (C): “ **Mechanical condition**”					**(B) Plumbing / Mechanical Equipment**	
	Extreme	Very Strong	Strong	Moderate	Equal	Moderate	Strong	Very Strong	Extreme
	9:1	7:1	5:1	3:1	1	1:3	1:5	1:7	1:9
*	○	○	○	○	○	○	○	○	○

6.

	(A) HVAC		Degree of importance with respect to (C): “ **Mechanical condition**”					**(B) Mechanical Systems**	
	Extreme	Very Strong	Strong	Moderate	Equal	Moderate	Strong	Very Strong	Extreme
	9:1	7:1	5:1	3:1	1	1:3	1:5	1:7	1:9
*	○	○	○	○	○	○	○	○	○

7.

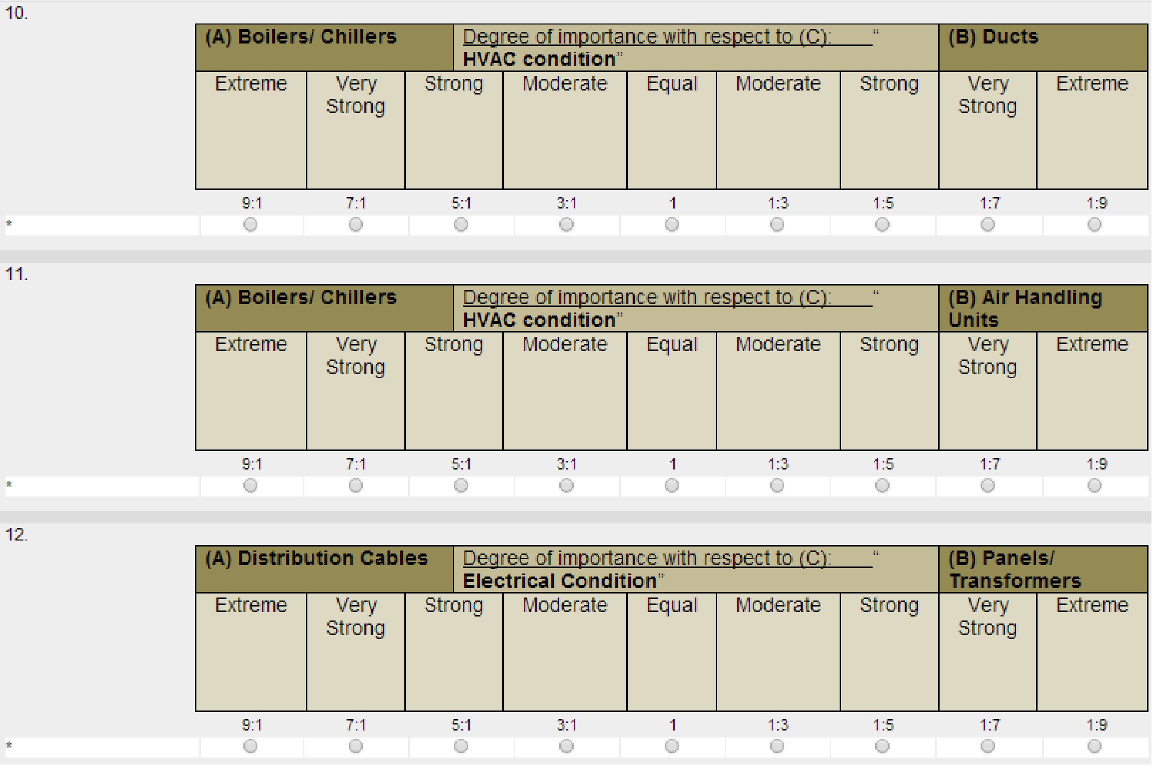
	(A) Pipes		Degree of importance with respect to (C) " **Mechanical Equipment/Plumbing**”					**(B) Track Drainage**	
	Extreme	Very Strong	Strong	Moderate	Equal	Moderate	Strong	Very Strong	Extreme
	9:1	7:1	5:1	3:1	1	1:3	1:5	1:7	1:9
*	○	○	○	○	○	○	○	○	○

8.

	(A) Pipes		Degree of importance with respect to (C): “ **Mechanical Equipment/Plumbing**”					**(B) Fire Extinguish**	
	Extreme	Very Strong	Strong	Moderate	Equal	Moderate	Strong	Very Strong	Extreme
	9:1	7:1	5:1	3:1	1	1:3	1:5	1:7	1:9
*	○	○	○	○	○	○	○	○	○

9.

	(A) Elevators		Degree of importance with respect to (C): “ **Mechanical Systems Condition**”					**(B) Escalators**	
	Extreme	Very Strong	Strong	Moderate	Equal	Moderate	Strong	Very Strong	Extreme
	9:1	7:1	5:1	3:1	1	1:3	1:5	1:7	1:9
*	○	○	○	○	○	○	○	○	○



10.

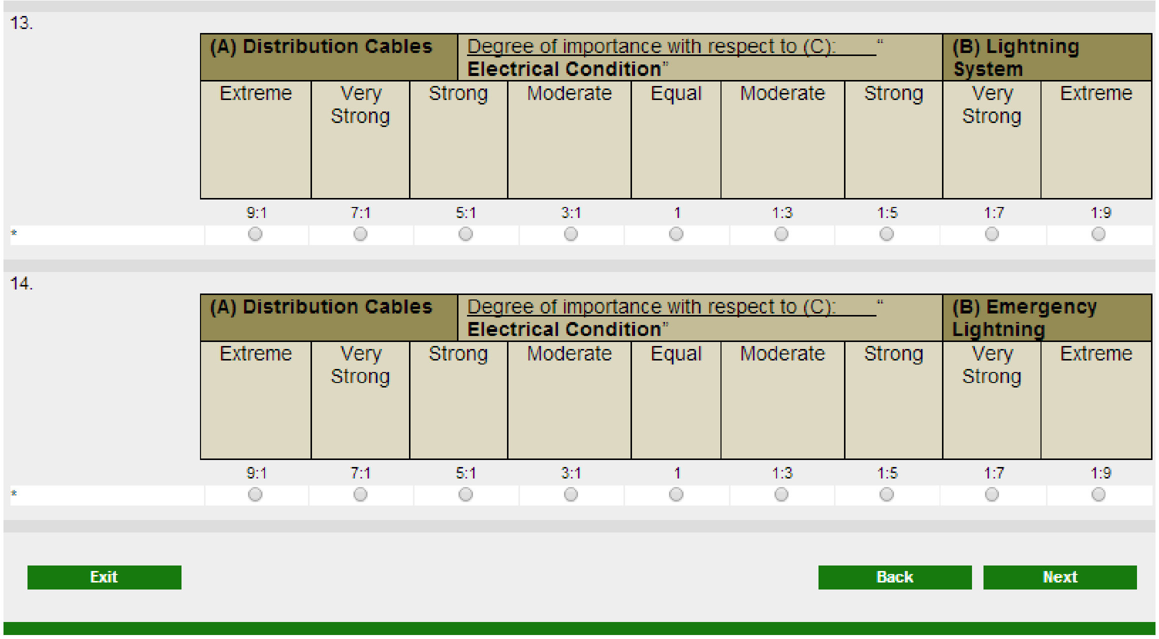
	(A) Boilers/ Chillers		Degree of importance with respect to (C): “ **HVAC condition**”					**(B) Ducts**	
	Extreme	Very Strong	Strong	Moderate	Equal	Moderate	Strong	Very Strong	Extreme
	9:1	7:1	5:1	3:1	1	1:3	1:5	1:7	1:9
*	○	○	○	○	○	○	○	○	○

11.

	(A) Boilers/ Chillers		Degree of importance with respect to (C): “ **HVAC condition**”					**(B) Air Handling Units**	
	Extreme	Very Strong	Strong	Moderate	Equal	Moderate	Strong	Very Strong	Extreme
	9:1	7:1	5:1	3:1	1	1:3	1:5	1:7	1:9
*	○	○	○	○	○	○	○	○	○

12.

	(A) Distribution Cables		Degree of importance with respect to (C): “ **Electrical Condition**”					**(B) Panels/ Transformers**	
	Extreme	Very Strong	Strong	Moderate	Equal	Moderate	Strong	Very Strong	Extreme
	9:1	7:1	5:1	3:1	1	1:3	1:5	1:7	1:9
*	○	○	○	○	○	○	○	○	○

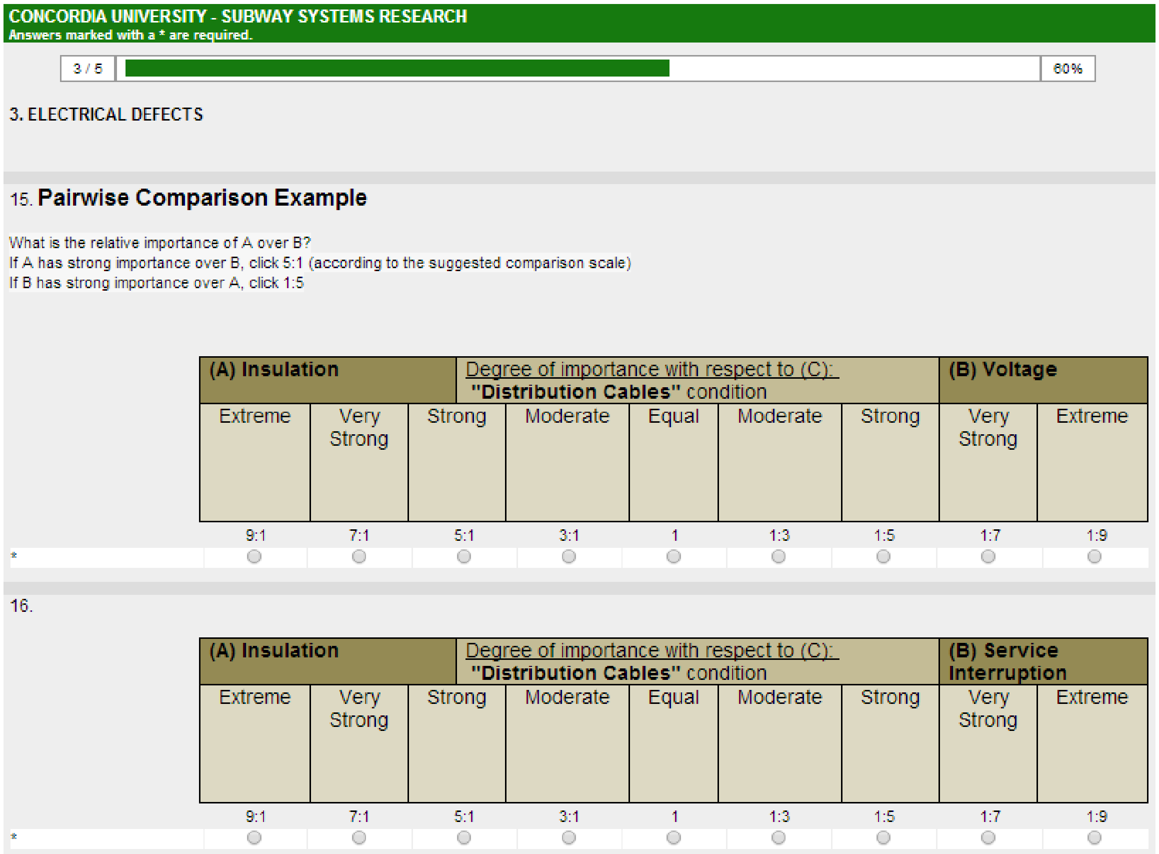


13.

	(A) Distribution Cables		Degree of importance with respect to (C): “ **Electrical Condition**”					**(B) Lightning System**	
	Extreme	Very Strong	Strong	Moderate	Equal	Moderate	Strong	Very Strong	Extreme
	9:1	7:1	5:1	3:1	1	1:3	1:5	1:7	1:9
*	○	○	○	○	○	○	○	○	○

14.

	(A) Distribution Cables		Degree of importance with respect to (C): “ **Electrical Condition**”					**(B) Emergency Lightning**	
	Extreme	Very Strong	Strong	Moderate	Equal	Moderate	Strong	Very Strong	Extreme
	9:1	7:1	5:1	3:1	1	1:3	1:5	1:7	1:9
*	○	○	○	○	○	○	○	○	○



CONCORDIA UNIVERSITY - SUBWAY SYSTEMS RESEARCH
Answers marked with a * are required.

3 / 5 60%

3. ELECTRICAL DEFECTS

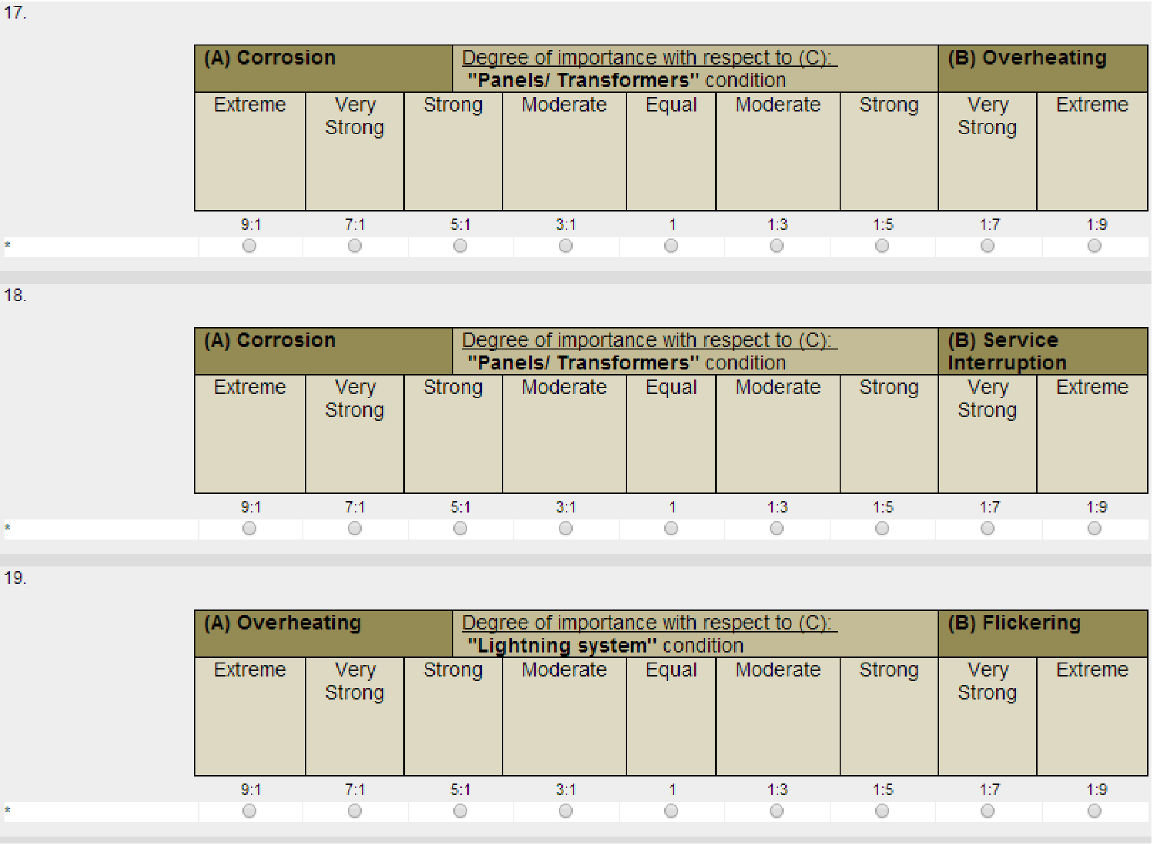
15. **Pairwise Comparison Example**

What is the relative importance of A over B?
If A has strong importance over B, click 5:1 (according to the suggested comparison scale)
If B has strong importance over A, click 1:5

	(A) Insulation		Degree of importance with respect to (C): **"Distribution Cables"** condition					**(B) Voltage**	
	Extreme	Very Strong	Strong	Moderate	Equal	Moderate	Strong	Very Strong	Extreme
	9:1	7:1	5:1	3:1	1	1:3	1:5	1:7	1:9
*	○	○	○	○	○	○	○	○	○

16.

	(A) Insulation		Degree of importance with respect to (C): **"Distribution Cables"** condition					**(B) Service Interruption**	
	Extreme	Very Strong	Strong	Moderate	Equal	Moderate	Strong	Very Strong	Extreme
	9:1	7:1	5:1	3:1	1	1:3	1:5	1:7	1:9
*	○	○	○	○	○	○	○	○	○



17.

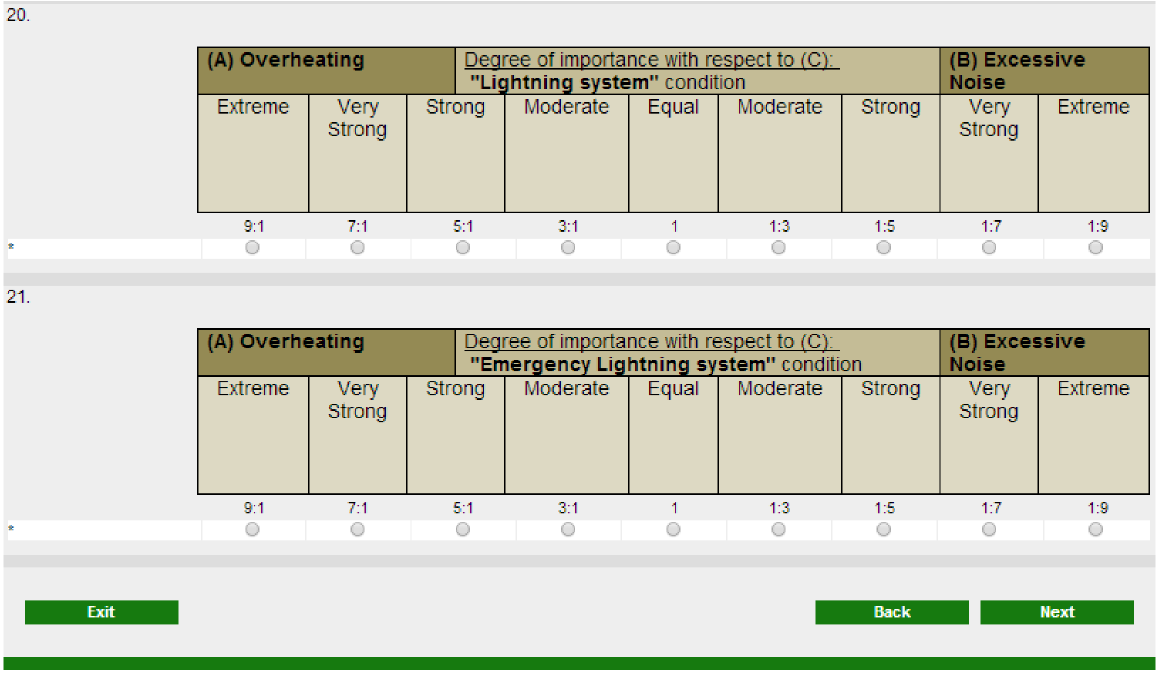
	(A) Corrosion			Degree of importance with respect to (C): **"Panels/ Transformers"** condition				**(B) Overheating**	
	Extreme	Very Strong	Strong	Moderate	Equal	Moderate	Strong	Very Strong	Extreme
	9:1	7:1	5:1	3:1	1	1:3	1:5	1:7	1:9
*	○	○	○	○	○	○	○	○	○

18.

	(A) Corrosion			Degree of importance with respect to (C): **"Panels/ Transformers"** condition				**(B) Service Interruption**	
	Extreme	Very Strong	Strong	Moderate	Equal	Moderate	Strong	Very Strong	Extreme
	9:1	7:1	5:1	3:1	1	1:3	1:5	1:7	1:9
*	○	○	○	○	○	○	○	○	○

19.

	(A) Overheating			Degree of importance with respect to (C): **"Lightning system"** condition				**(B) Flickering**	
	Extreme	Very Strong	Strong	Moderate	Equal	Moderate	Strong	Very Strong	Extreme
	9:1	7:1	5:1	3:1	1	1:3	1:5	1:7	1:9
*	○	○	○	○	○	○	○	○	○

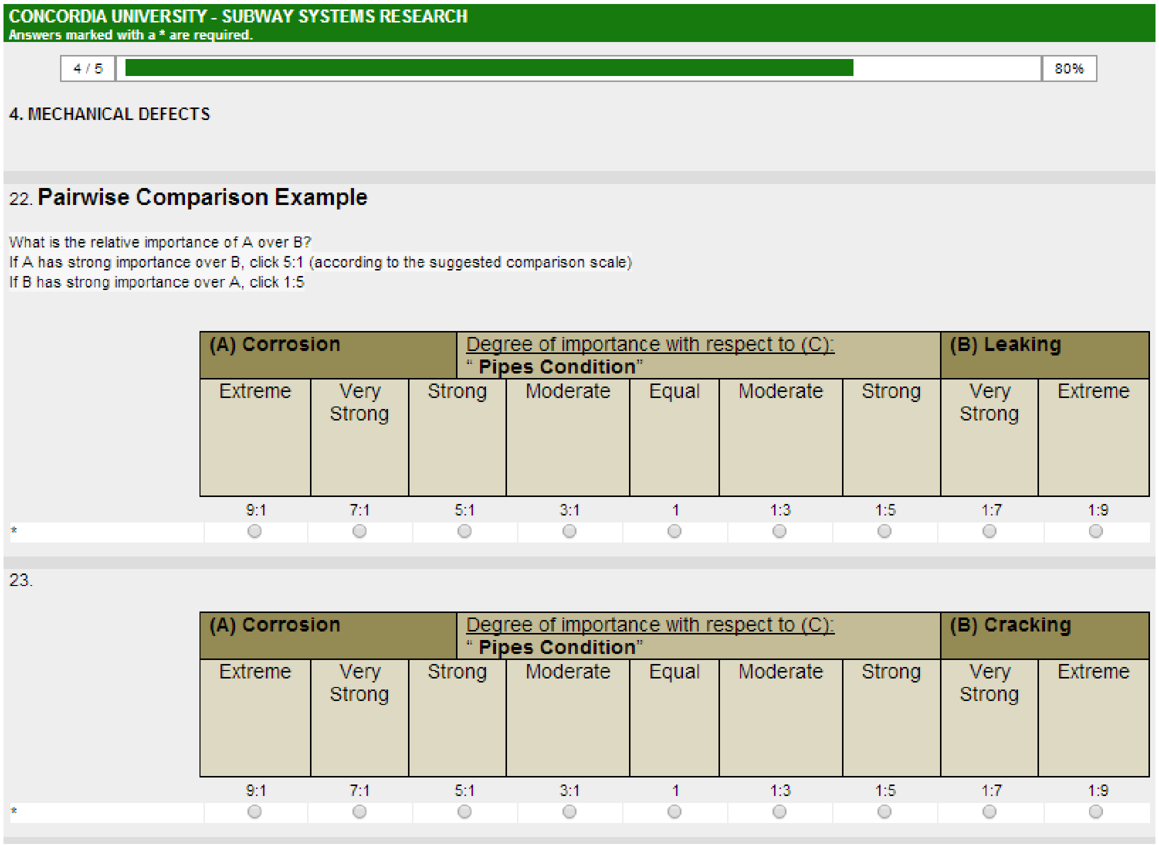


20.

	(A) Overheating			Degree of importance with respect to (C): **"Lightning system"** condition				**(B) Excessive Noise**	
	Extreme	Very Strong	Strong	Moderate	Equal	Moderate	Strong	Very Strong	Extreme
	9:1	7:1	5:1	3:1	1	1:3	1:5	1:7	1:9
*	○	○	○	○	○	○	○	○	○

21.

	(A) Overheating			Degree of importance with respect to (C): **"Emergency Lightning system"** condition				**(B) Excessive Noise**	
	Extreme	Very Strong	Strong	Moderate	Equal	Moderate	Strong	Very Strong	Extreme
	9:1	7:1	5:1	3:1	1	1:3	1:5	1:7	1:9
*	○	○	○	○	○	○	○	○	○



CONCORDIA UNIVERSITY - SUBWAY SYSTEMS RESEARCH

Answers marked with a * are required.

4 / 5 80%

4. MECHANICAL DEFECTS

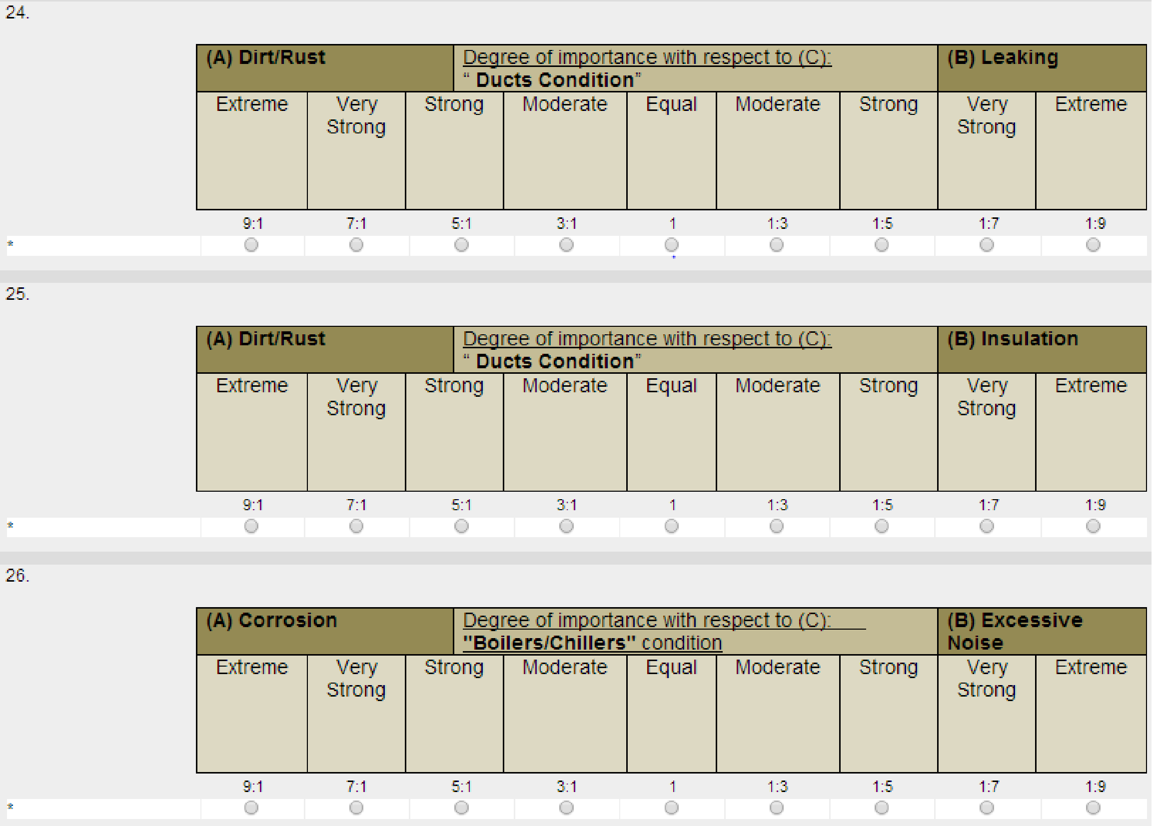
22. **Pairwise Comparison Example**

What is the relative importance of A over B?
If A has strong importance over B, click 5:1 (according to the suggested comparison scale)
If B has strong importance over A, click 1:5

	(A) Corrosion			Degree of importance with respect to (C): " **Pipes Condition**"				**(B) Leaking**	
	Extreme	Very Strong	Strong	Moderate	Equal	Moderate	Strong	Very Strong	Extreme
	9:1	7:1	5:1	3:1	1	1:3	1:5	1:7	1:9
*	○	○	○	○	○	○	○	○	○

23.

	(A) Corrosion			Degree of importance with respect to (C): " **Pipes Condition**"				**(B) Cracking**	
	Extreme	Very Strong	Strong	Moderate	Equal	Moderate	Strong	Very Strong	Extreme
	9:1	7:1	5:1	3:1	1	1:3	1:5	1:7	1:9
*	○	○	○	○	○	○	○	○	○



24.

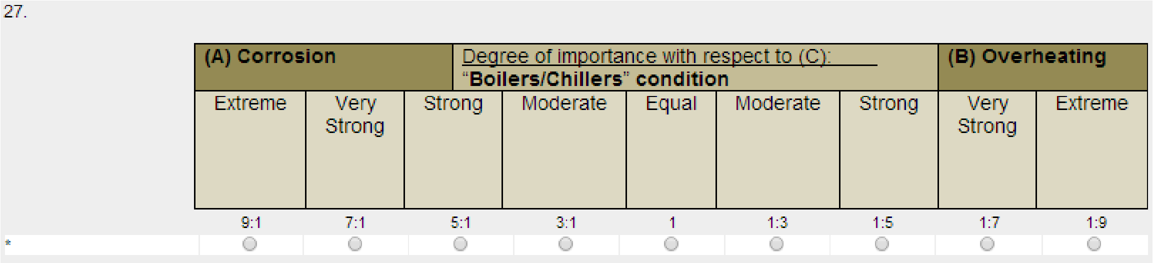
	(A) Dirt/Rust			Degree of importance with respect to (C): " **Ducts Condition**"				**(B) Leaking**	
	Extreme	Very Strong	Strong	Moderate	Equal	Moderate	Strong	Very Strong	Extreme
	9:1	7:1	5:1	3:1	1	1:3	1:5	1:7	1:9
*	○	○	○	○	○	○	○	○	○

25.

	(A) Dirt/Rust			Degree of importance with respect to (C): " **Ducts Condition**"				**(B) Insulation**	
	Extreme	Very Strong	Strong	Moderate	Equal	Moderate	Strong	Very Strong	Extreme
	9:1	7:1	5:1	3:1	1	1:3	1:5	1:7	1:9
*	○	○	○	○	○	○	○	○	○

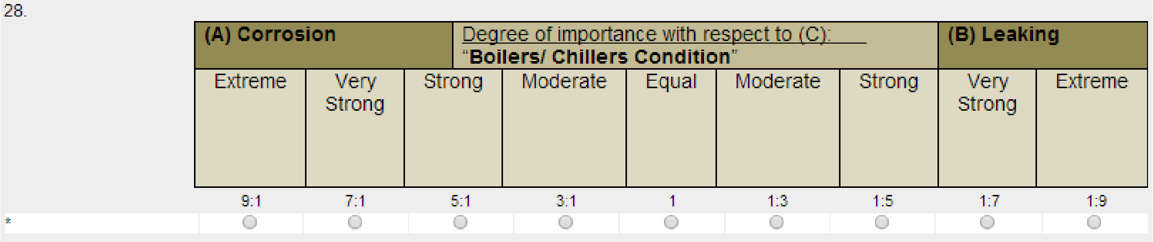
26.

	(A) Corrosion			Degree of importance with respect to (C): **"Boilers/Chillers"** condition				**(B) Excessive Noise**	
	Extreme	Very Strong	Strong	Moderate	Equal	Moderate	Strong	Very Strong	Extreme
	9:1	7:1	5:1	3:1	1	1:3	1:5	1:7	1:9
*	○	○	○	○	○	○	○	○	○



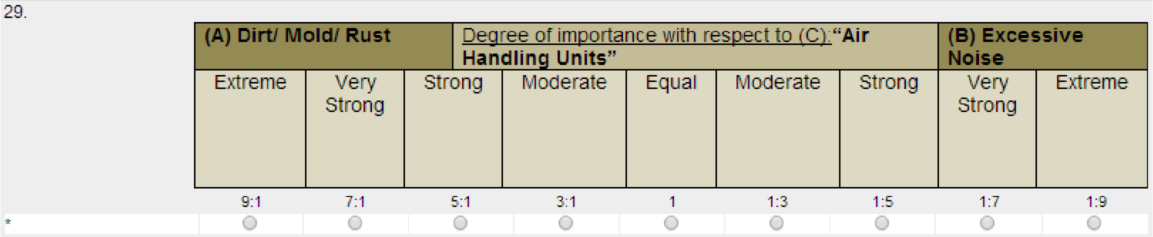
27.

	(A) Corrosion		Degree of importance with respect to (C): “**Boilers/Chillers**” **condition**					**(B) Overheating**	
	Extreme	Very Strong	Strong	Moderate	Equal	Moderate	Strong	Very Strong	Extreme
	9:1	7:1	5:1	3:1	1	1:3	1:5	1:7	1:9
*	○	○	○	○	○	○	○	○	○



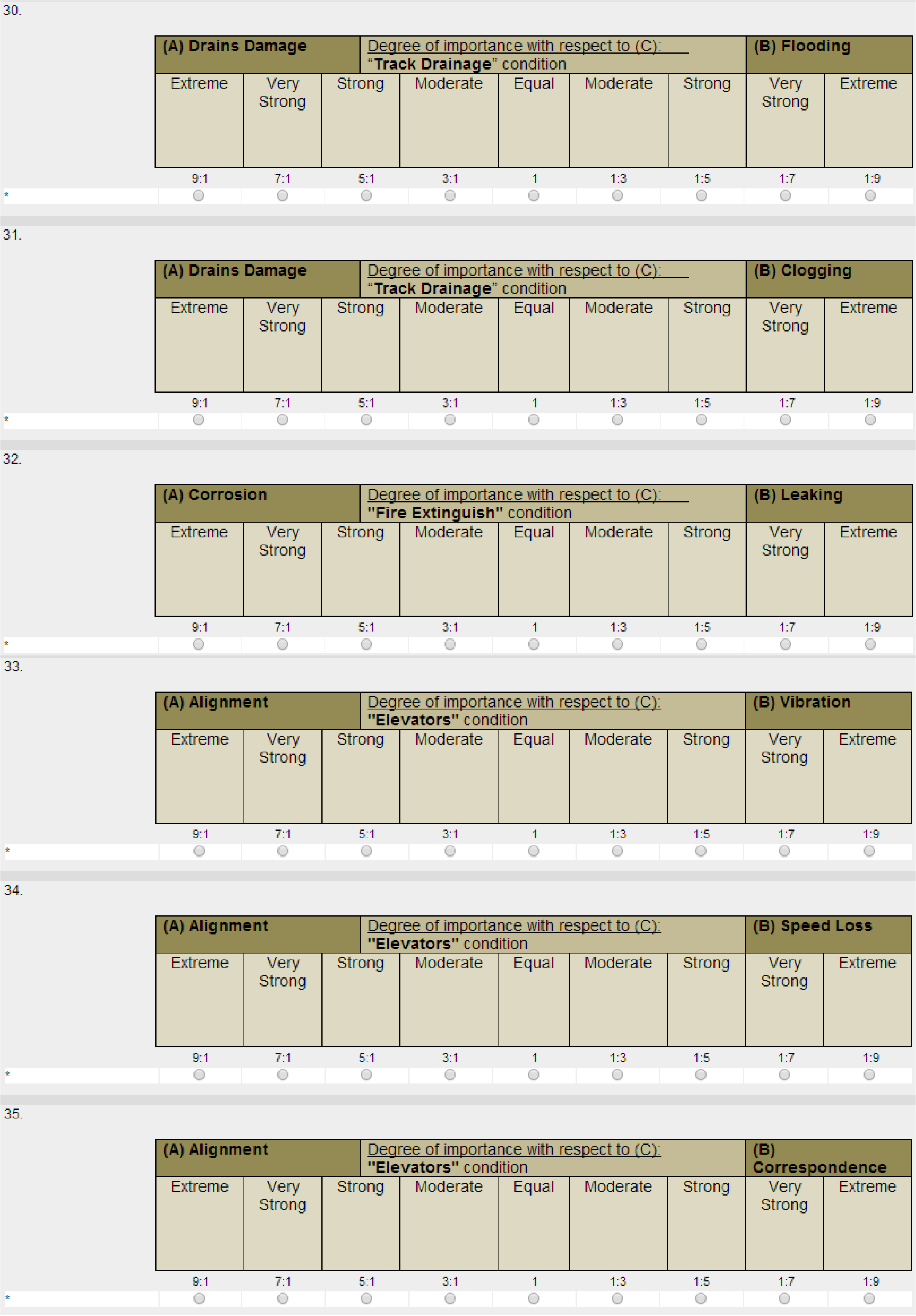
28.

	(A) Corrosion		Degree of importance with respect to (C): “**Boilers/ Chillers Condition**”					**(B) Leaking**	
	Extreme	Very Strong	Strong	Moderate	Equal	Moderate	Strong	Very Strong	Extreme
	9:1	7:1	5:1	3:1	1	1:3	1:5	1:7	1:9
*	○	○	○	○	○	○	○	○	○



29.

	(A) Dirt/ Mold/ Rust		Degree of importance with respect to (C):**“Air Handling Units”**					**(B) Excessive Noise**	
	Extreme	Very Strong	Strong	Moderate	Equal	Moderate	Strong	Very Strong	Extreme
	9:1	7:1	5:1	3:1	1	1:3	1:5	1:7	1:9
*	○	○	○	○	○	○	○	○	○



30.

	(A) Drains Damage		Degree of importance with respect to (C): “**Track Drainage**” condition					**(B) Flooding**	
	Extreme	Very Strong	Strong	Moderate	Equal	Moderate	Strong	Very Strong	Extreme
	9:1	7:1	5:1	3:1	1	1:3	1:5	1:7	1:9
*	○	○	○	○	○	○	○	○	○

31.

	(A) Drains Damage		Degree of importance with respect to (C): “**Track Drainage**” condition					**(B) Clogging**	
	Extreme	Very Strong	Strong	Moderate	Equal	Moderate	Strong	Very Strong	Extreme
	9:1	7:1	5:1	3:1	1	1:3	1:5	1:7	1:9
*	○	○	○	○	○	○	○	○	○

32.

	(A) Corrosion		Degree of importance with respect to (C): **"Fire Extinguish"** condition					**(B) Leaking**	
	Extreme	Very Strong	Strong	Moderate	Equal	Moderate	Strong	Very Strong	Extreme
	9:1	7:1	5:1	3:1	1	1:3	1:5	1:7	1:9
*	○	○	○	○	○	○	○	○	○

33.

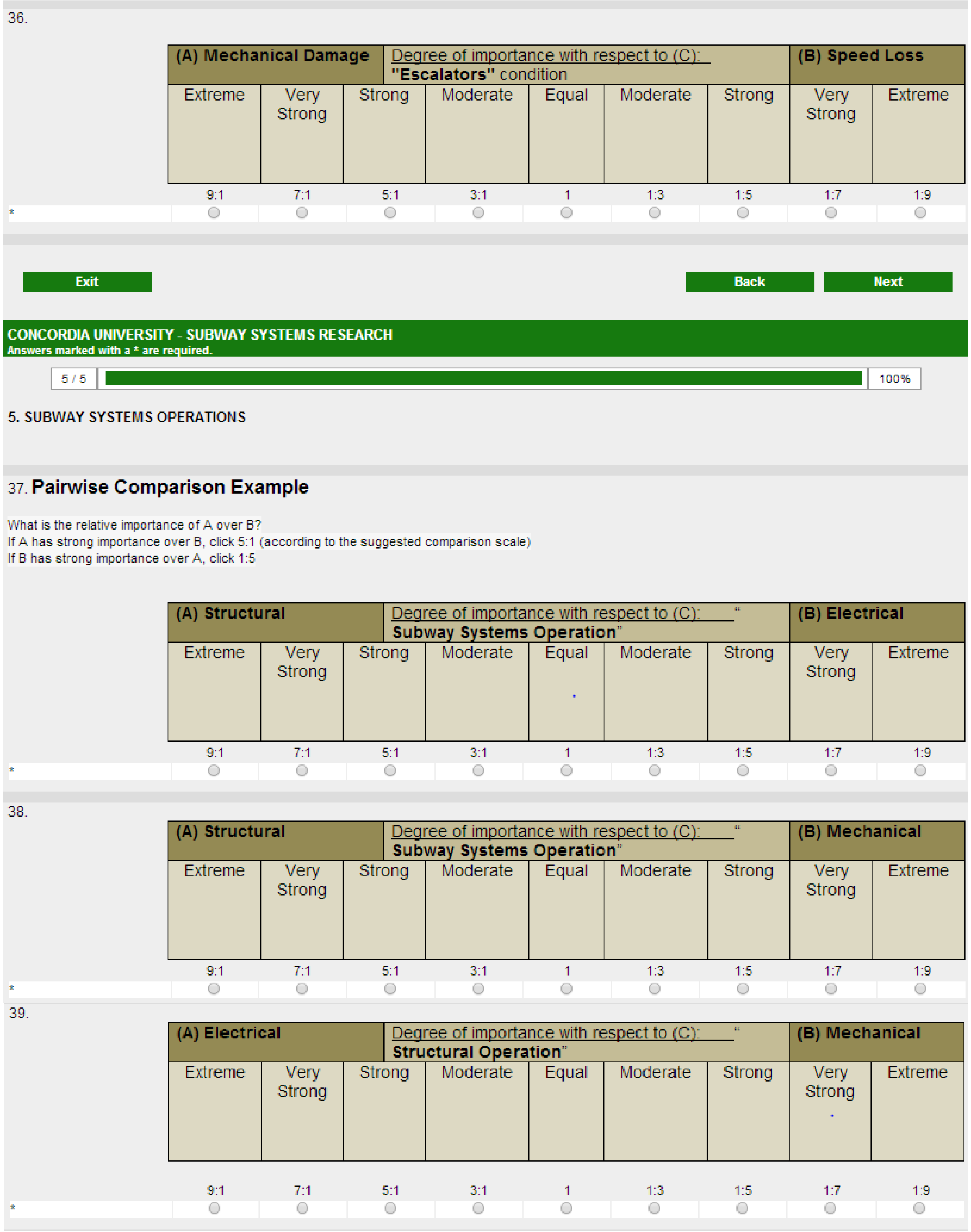
	(A) Alignment		Degree of importance with respect to (C): **"Elevators"** condition					**(B) Vibration**	
	Extreme	Very Strong	Strong	Moderate	Equal	Moderate	Strong	Very Strong	Extreme
	9:1	7:1	5:1	3:1	1	1:3	1:5	1:7	1:9
*	○	○	○	○	○	○	○	○	○

34.

	(A) Alignment		Degree of importance with respect to (C): **"Elevators"** condition					**(B) Speed Loss**	
	Extreme	Very Strong	Strong	Moderate	Equal	Moderate	Strong	Very Strong	Extreme
	9:1	7:1	5:1	3:1	1	1:3	1:5	1:7	1:9
*	○	○	○	○	○	○	○	○	○

35.

	(A) Alignment		Degree of importance with respect to (C): **"Elevators"** condition					**(B) Correspondence**	
	Extreme	Very Strong	Strong	Moderate	Equal	Moderate	Strong	Very Strong	Extreme
	9:1	7:1	5:1	3:1	1	1:3	1:5	1:7	1:9
*	○	○	○	○	○	○	○	○	○



36.

	(A) Mechanical Damage		Degree of importance with respect to (C): **"Escalators"** condition					**(B) Speed Loss**	
	Extreme	Very Strong	Strong	Moderate	Equal	Moderate	Strong	Very Strong	Extreme
	9:1	7:1	5:1	3:1	1	1:3	1:5	1:7	1:9
*	○	○	○	○	○	○	○	○	○

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Answers marked with a * are required.

5 / 5 100%

5. SUBWAY SYSTEMS OPERATIONS

37. **Pairwise Comparison Example**

What is the relative importance of A over B?
If A has strong importance over B, click 5:1 (according to the suggested comparison scale)
If B has strong importance over A, click 1:5

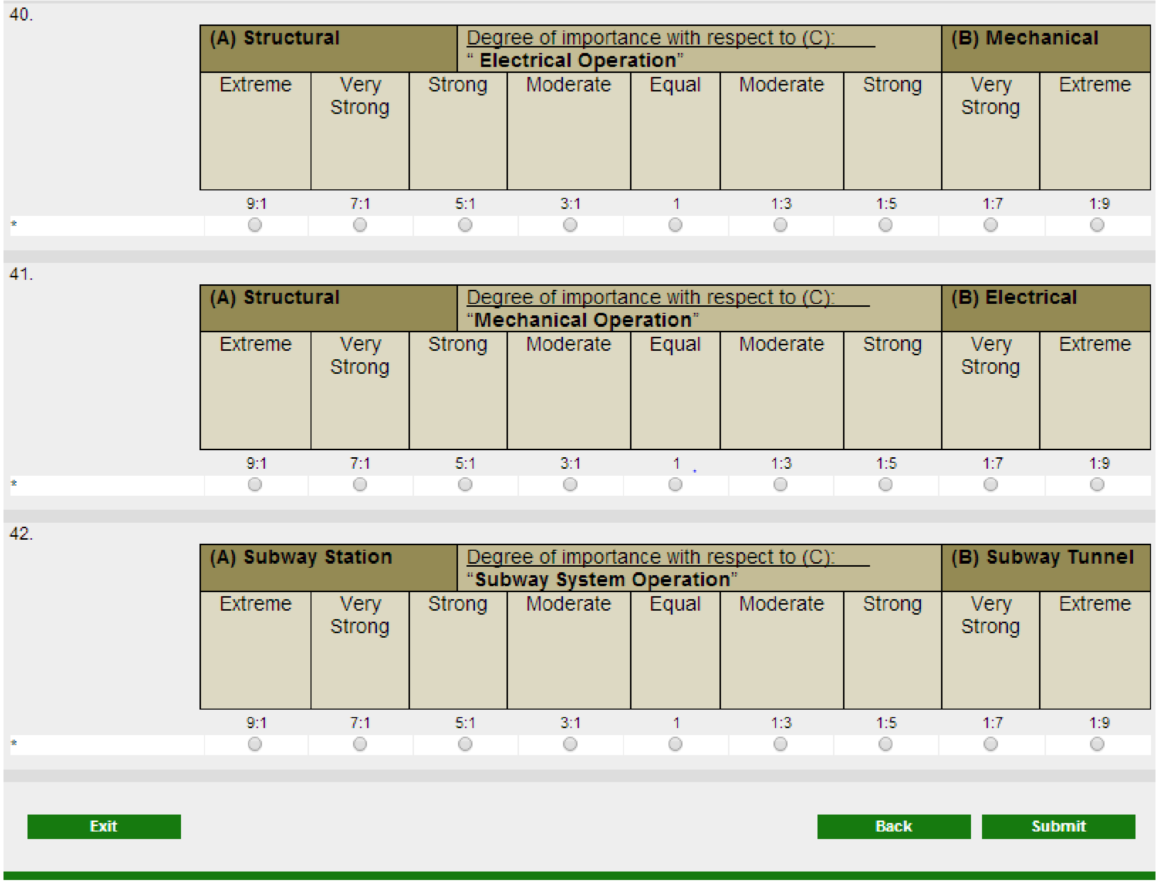
	(A) Structural		Degree of importance with respect to (C): " **Subway Systems Operation**"					**(B) Electrical**	
	Extreme	Very Strong	Strong	Moderate	Equal	Moderate	Strong	Very Strong	Extreme
	9:1	7:1	5:1	3:1	1	1:3	1:5	1:7	1:9
*	○	○	○	○	○	○	○	○	○

38.

	(A) Structural		Degree of importance with respect to (C): " **Subway Systems Operation**"					**(B) Mechanical**	
	Extreme	Very Strong	Strong	Moderate	Equal	Moderate	Strong	Very Strong	Extreme
	9:1	7:1	5:1	3:1	1	1:3	1:5	1:7	1:9
*	○	○	○	○	○	○	○	○	○

39.

	(A) Electrical		Degree of importance with respect to (C): " **Structural Operation**"					**(B) Mechanical**	
	Extreme	Very Strong	Strong	Moderate	Equal	Moderate	Strong	Very Strong	Extreme
	9:1	7:1	5:1	3:1	1	1:3	1:5	1:7	1:9
*	○	○	○	○	○	○	○	○	○



40.

	(A) Structural		Degree of importance with respect to (C): “ **Electrical Operation**”					**(B) Mechanical**	
	Extreme	Very Strong	Strong	Moderate	Equal	Moderate	Strong	Very Strong	Extreme
	9:1	7:1	5:1	3:1	1	1:3	1:5	1:7	1:9
*	○	○	○	○	○	○	○	○	○

41.

	(A) Structural		Degree of importance with respect to (C): “**Mechanical Operation**”					**(B) Electrical**	
	Extreme	Very Strong	Strong	Moderate	Equal	Moderate	Strong	Very Strong	Extreme
	9:1	7:1	5:1	3:1	1	1:3	1:5	1:7	1:9
*	○	○	○	○	○	○	○	○	○

42.

	(A) Subway Station		Degree of importance with respect to (C): “**Subway System Operation**”					**(B) Subway Tunnel**	
	Extreme	Very Strong	Strong	Moderate	Equal	Moderate	Strong	Very Strong	Extreme
	9:1	7:1	5:1	3:1	1	1:3	1:5	1:7	1:9
*	○	○	○	○	○	○	○	○	○