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Defect- and Component- Based Assessment Model for Manholes

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Abstract

Manholes are significant assets in sewer networks; yet, their assessment is receiving little attention compared to sewer pipelines. Recent studies started to emerge in this area to preserve manholes from any malfunction and possible failure. It is reported that more than three-million manholes in the US are structurally weak and are prone to failure. Therefore, the main objective of this study is to present a condition assessment model for manholes. The methodology is based on integrating the Quality Function Deployment (QFD), Decision-Making Trial Evaluation Laboratory (DEMATEL) techniques to study the cause and effect relation between the defects in the nine components of the manhole. The relative importance weights of the components are found by deploying the Analytic Network Process (ANP) and are used to compute the overall condition of the asset. Based on the results, the roots have the highest influence power in many of the components. In addition, wall, cone, cover and frame and seals components have higher importance weights compared to remaining components. This model is tested on an actual case study from the city of Edmonton, Canada and validated with actual values. The model produced an average validity percentage (AVP) of 76.24%. The developed model is expected to enhance the assessment of manholes and therefore provide solid conclusions. Besides, the model provides a backward analysis to pinpoint critical components in the manhole. Consequently, better decisions are made pertinent to maintenance, rehabilitation, and replacement actions.

Keywords: Analytic Network Process (ANP); condition assessment; Decision-Making Trial Evaluation Laboratory **(**DEMATEL); manhole; Quality Function Deployment (QFD)

1. **Introduction**

Preserving aging sewers is a major task for municipalities to prevent catastrophic collapses and malfunction of sewer systems (Anbari et al., 2017). Yet, these critical assets are neglected by many governments despite their health and environmental benefits (Kirkham et al., 2000). According to the American Society of Civil Engineers (ASCE), the condition of the wastewater system in the United States (US) is D+ (ASCE, 2017). With the efforts accomplished in maintaining sewers, many researchers and agencies developed prediction and defect-based assessment models to aid decision makers in their rehabilitation plans. However, the main attention was driven toward the assessment of buried pipelines and very few studies were pertinent to manholes (Sever et al., 2013).

2. Manholes are significant elements in infrastructure networks as they provide access to sewer maintenance (Sever et al., 2013) and accommodate all geometrical changes of sewers (Martino et al., 2002). They are concrete assets and therefore prone to deterioration similar to buried linear elements (Hughes, 2002). Nevertheless, the concentrations of hydrogen sulfide (H_2S) emissions are less due to larger geometrical dimensions of manholes compared to pipelines (Tran et al., 2011). Nevertheless, the accumulated emissions of H_2S can be a primary reason for the manhole failure due to continuous corrosion and degradation of the manhole components. According to Sever et al. (2013), more than three-million manholes have structural deficiencies in the US and in need of immediate interventions. Furthermore, defective manholes are a main source of inflow/infiltration (I/I) to the collection networks and can contribute up to 50% of the inflow within the collection system (Hughes, 2002). As a result, the designed flow will vary and results in additional wastewater treatment costs. Not only but also, the incapability to withstand the excessive I/I could lead to sewer flooding (Lee et al., 2013) and jeopardize the environment and habitats. Thus, a comprehensive manhole assessment shall be established to inform decision-makers about the current conditions of the manholes. This is, in fact, a leading process toward effective prioritization and rehabilitation plans to maximize their efficiency and meet the required level of service (Vladeanu and Matthews, 2018). Background

The National Association of Sewer Service Companies (NASSCO) released a manhole condition assessment protocol in 2010 based on the response of the industry's demand for a program to code and assess the manhole defects. Several agencies in North America commenced utilizing the developed protocol to assess sewer manholes. The methodology is similar to the Pipeline

Assessment and Certification Program (PACP) as it incorporates similar PACP defect coding system. It consists of two different inspection levels: level 1 and level 2. Level 1 is based on gathering general information and have general condition evaluation. However, level 2 relies on detailed information gathering and detailed defects recording. The grades range between 1 and 5, where 1 corresponds to acceptable structural condition and 5 describes a failed or failure imminent condition.

Nelson et al. (2010), however, described the analysis processes of the manhole data in estimating the I/I to assess the manhole condition. The authors suggested flow rates estimates for manholes for each defect type in each manhole component. A total score was then calculated by multiplying the flow rate by the condition score. Later, manhole prioritization model was based on the total score found and the location of the manhole itself. In addition, Hughes (2009) relied on the I/I estimation and the structural condition flow to determine the condition of sewer manholes. The author relied on a score from 1 to 5 to grade the divided manhole components' structural and I/I defects. The linguistic grades for I/I were No I/I, Minor I/I, Moderate I/I, Heavy I/I and Severe I/I. Furthermore, the structural defects were based on cracks and fractures and general deterioration defects. The author also provided decision matrixes for manhole rehabilitation actions.

In another related work, Daher et al. (2017) suggested a scheme to evaluate manholes condition after suggesting structural, operational, and installation and rehabilitation defects. In general, the overall methodology of the study was based on fuzzy expert system, Hierarchal Evidential Reasoning and (HER) and Analytic Network Process (ANP). The author considered five different scales to conclude the overall condition of the manhole. The scale used was Excellent, Good, Fair, Poor and Critical. Bakry et al. (2016), however, developed a multiple regression condition prediction model for rehabilitated sewer manholes. The model was able to predict the operational and structural conditions of the assets considering distinct variables. The operational prediction model relied on the overall manhole depth, rehabilitation age, chimney material type, radius, and shape. Beside these variables, the structural prediction model considered the chamber material type. Despite the efforts devoted in assessing sewer manholes, the current researches are limited, as multiple defects and manhole components are neglected. Not only but also, a wide range of the formalized protocols considered equivalent weights to manhole components, given that some components of the manholes could be more important than the others. Furthermore, distinct codes considered the application of peak and mean scores in the evaluation process, which result in incomplete representation of the overall manhole condition (Daher et al., 2017). Although NASSCO sewer ratings are good in some applications, the accuracy in reflecting the true severity and overall condition is a major concern (Vladeanu and Matthews, 2018). Besides, predicting the condition of sewer manholes using some physical, operational and environmental characteristics do not reflect the actual deterioration process of the asset (Elmasry et al., 2017).

As a result, a comprehensive assessment of manholes is required to enhance the accuracy in calculating the overall condition of the asset, which is one of the main inputs in a selecting a rehabilitation method (Matthews et al., 2018). This study aims at developing component- and defect- based condition assessment model for manholes. The model integrates the Quality Function Deployment (QFD) and the Decision-Making Trial Evaluation Laboratory **(**DEMATEL) methods to compute a condition index for each component. Subsequently, using the ANP method, all conditions are aggregated through the relative importance weights of the manhole components to describe the overall condition of the asset. Besides informing decision makers about the overall condition of the manholes, the methodology offers a backward analysis to pinpoint critical manhole components

3. Methods and Materials

3.1 QFD

QFD is a method conducted to transfer the customer needs into technical requirements (Sullivan, 1986). The method was firstly developed in Japan in 1966 by Yoji Akao; nevertheless, the approach was not formalized in quality control planning until 1972 (Hofmeister, 1991). Since then, QFD approach was rapidly spread across Japan and the US (Hofmeister, 1991). QFD is a Total Quality Management (TQM) as it requires the inclusion of customer needs into project design targets apart from the basic projects' requirements (Dikmen et al., 2005). It focuses on implementing the voice of the customer, a critical step (Costa et al., 2000), after assessing their needs, which are usually determined by interviews and/or focus groups or surveys, to ensure their satisfaction (Dikmen et al., 2005).

The formulation of the QFD approach starts with the determination of the product policy and the end-user needs into a basic concept. Therefore, design requirements are established to form the "WHAT's", which in turn establishes the component characteristics "HOW's" of the product design. A matrix is then constructed to study the relationship between the HOW's and the WHAT's (Govers, 1996). After that, the absolute weights are determined by aggregating the HOW's and WHAT's through the use of the factors in the matrix established earlier. Consequently, the House of Quality (HOQ) is then finalized to better represent the problem in hand.

QFD is utilized in this study as a tool in the condition assessment of manholes and will be restructured to suit its application in infrastructure assessment. Thus, in the context of this research, each component is considered as follows (Alsharqawi et al., 2016):

- WHAT's are the condition severities. In this research, five different severities are considered: excellent, very good, fair, poor and critical. These severities concludes the components and the overall asset's condition.
- HOW's represents the defects considered in each asset under assessment in percentagewise. These are obtained from the inspection reports.
- Relationship matrix is the top roof component of the QFD approach. It establishes the relationship between the defects in concern.
- Absolute Weights are the weights of the WHAT's, which are concluded after aggregating the HOW's and each WHAT.
- HOQ represents the complete application of the QFD. Since this study divides the manhole into nine different components, each component will have a unique HOQ that includes the HOW's and WHAT's based on the considered defects.

2.1 DEMATEL

Davies et al. (2001) discussed several factors that could lead to the structural collapse of sewer pipelines. These factors could be influencing or influenced based on its propagation in the system. One basic comparison of these two categories is between cracks and fractures in sewer environment. According to Davies et al. (2001), erosion voids can lead to deformation and then cracks will propagate. Later, the continuous induced loads will reform cracks to fractures. Hence, one can conclude that in the explained system, erosion voids is an influencing defect and fractures is an influenced defect. Yet, sewers are subject to multiple defects and the influence power varies from one defect to the other. One method that can distinguish the influencing and influenced defects in any manhole component is the DEMATEL approach. Besides, it is capable to supply the influencing and influenced powers of each defect.

DEMATEL was developed by the Science and Human Affairs Program of the Battelle Memorial Institute of Geneva between 1972 made 1976 to solve complicated problems (Tzeng et al., 2007). This method is capable to establish an interdependency relationship between the participating variables in a cause and effect concept to conclude the causing and effecting variables (Tzeng et al., 2007). Therefore, the result of the method could find the central components of the problem. This technique is based on a questionnaire that an expert needs to answer. The more the responses are, the better the results are as they compile several professional opinions in the domain. After receiving the responses, the average influence matrix is constructed, which shows the influence of one element in the system to the other. The influence is represented by 0, 1, 2, 3 and 4 which indicates "no influence", "low influence", "medium influence", "high influence" and "extreme influence". Next, the normalized influence matrix is assembled which derives the total influence matrix. As a result, the cause and effect contribution of each element in the system is consummated. The basic steps to complete the DEMATEL application in this study is as follows (Shieh et al., 2010; Tzeng et al., 2007):

1- Find the average matrix. The average matrix is calculated from the respondents of the questionnaire to evaluate the direct and indirect influence between any two participating elements; herein, are the defects in the system. The influence is represented by certain values which are tabulated in Table 1 along with their definitions. The lower is the number, lower is the influence and vice versa.

Influence Number	**Definition**
0	No Influence
1	Low Influence

2	Medium Influence
3	High Influence
4	Extreme Influence

Table 1. DEMATEL Influence Values and Definitions

The degree of which the respondents believe that factor i is affected by factor j is given by the notation x_{ij}. For example, if an expert assigns a value of 3 when comparing the influence of deformation to vertical crack, this means that deformation has high influence in initiating the crack. However, for $i = j$, which are the diagonal values in a matrix, the values are set to zero. For each respondent, n x n non-negative matrix can be established as $X^k = [x^k_{ij}]$, where k is the number of participating respondents with $1 \leq k \leq H$, and n is the number of factors. As a result, X^1, X^2... X^H are the number of matrices found from each respondent. Therefore, the values of each x_{ij} in each matrix is computed through the average as per equation 1.

$$a_{ij} = \frac{1}{H}\sum_{k=1}^{H} x_{ij}^{k} \qquad [1]$$

The average matrix is displayed in the HOQ as the top roof triangle, which is originally the correlation matrix in basic QFD method. Figure 1 shows the average influence matrix of a system comprised of four elements. Taking element 2 and 3 as an illustration, a_{23} is the influence of element 2 on factor 3. However a_{32} is the influence of element 3 on factor 2. In fact, the zeros in the triangle are the diagonal values of the matrix which are always zero.

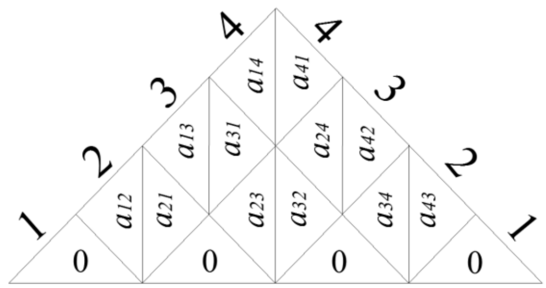


Figure 1. Relationship Matrix in HOQ

2- Calculate the normalized direct influence relation matrix *D* from the average matrix found in step 1 and according to equation 2. To do so, identify the maximum value from summing the a_{ij} values in the rows and in the columns. The maximum value will be used to compute matrix *D*.

$$S = \frac{1}{\underset{1 \le i \le n}{Max} \sum_{j=1}^{n} a_{ij}} \qquad [2]$$

3- Calculate the total relation influence matrix. The total relation influence matrix *T* is calculated by equation 3.

$$T = D\,(I - D)^{-1} \qquad [3]$$

where *I* is the identity matrix. Define *r* and *c* be *n x* 1 and 1 *x n* vectors representing the sum of rows and sum of columns of the total relation matrix *T*, respectively. Consider r_i be the sum of *i*th row in matrix *T*, then r_i concludes both direct and indirect effects given by factor *i* to the other factors. If c_j denotes the sum of *j*th column in matrix *T*, then c_j shows both direct and indirect effects by factor *j* from the other factors. When $j = i$, the sum $(r_i + c_j)$ shows the total effects given and received by factor *i*. In other words, it represents the total cause and effect relation in the whole system. However, the difference $(r_i - c_j)$ translate the net effect that factor *i* contributes to the system. If the value computed is positive, then the factor is a cause or influencing. On the other hand, if the calculated value is negative, then the factor is an effect or influenced.

4- Consider setting up a threshold to filter out negligible effects. Nevertheless, in this research, setting up a threshold will not be considered as all participating elements are assumed to be significant in assessing the condition of the sewer assets. Neglecting one defect can provide unreliable conclusions when it comes to rehabilitation actions.

2.2 ANP

ANP is one of the multi criteria decision making process techniques that is widely used. It is based on considering the decision makers' judgments on the factors involved in a certain system. The root of ANP method is the Analytic Hierarchy Process (AHP) which is developed by Saaty in the late 1960's, which is a general theory of measurements (Saaty and Vargas, 2002). It is used to find relative priorities on absolute scales from both discrete and continuous paired comparisons in multilevel hierarchic structures (Hawari et al., 2016). The comparison could be established by actual measurements or by a relative strength of preference of feelings. Since many problems cannot be structured hierarchically, ANP was designed to consider the interaction and dependence of elements involved in the system or network. In other words, AHP used to establish a comparison in a vertical direction unlike ANP that considers a comparison in vertical and horizontal directions.

ANP method was applied in different applications related to strategic planning, project management, fund allocation, human resources and research and development problems and supplied satisfactory results (Daher et al., 2017). In addition, this method was adopted in assessing several infrastructure assets and the methodologies supplied minimal errors compared to actual values. For instance, Hawari et al. (2016) proposed a model that assessed the condition of free-flow and pressurized sewer pipelines by integrating the fuzzy logic and ANP. Additionally, El

Chanati et al. (2015) modeled a performance assessment methodology to assess water pipelines by aggregating several identified factors using ANP method. Also, the condition of oil and gas pipelines were evaluated using the ANP application (El-Abbasy et al., 2015). Due to the successful implementations of ANP in infrastructure management, this study adopts ANP to compare the manhole's components and aggregate their condition indexes to supply an overall manhole index.

The first step of the ANP method is identifying the system to be analyzed and decompose it through a set of hierarchies or networks. Later, paired comparison judgments in the AHP/ANP are applied to pairs of homogeneous elements. In many cases, the preferences or the judgments are established by a questionnaire given to experts. The fundamental scale of values to represent the intensities of judgments are shown in Table 2.

Intensity of Importance	Definition	Explanation
1	Equal Importance	Two attributes contribute equally to the objective
2	Weak	Intermediate values
3	Moderate Importance	Experience and judgment slightly favor one activity over another
4	Moderate Plus	Intermediate values
5	Strong Importance	Experience and judgment strongly favor one activity over another
6	Strong Plus	Intermediate values
7	Very Strong or Demonstrated Importance	An activity is favored very strongly over another; its dominance demonstrated in practice
8	Very, Very Strong	Intermediate values
9	Extreme Importance	The evidence favoring one activity over another is of the highest possible order of affirmation
Reciprocals of Above	If activity *i* has one of the above nonzero numbers assigned to it when compared with activity *j*, then *j* has the reciprocal value when compared with *i*	

Table 2. Intensity of Importance Scales for AHP/ANP

Suppose that an element Z in an arbitrary system is given a relative importance of k compared to element C, then the relative importance of element C when compared to element Z is 1/k. After collecting the pairwise comparison from the experts, the unweighted matrix considering the relative importance weights is constructed. The next step is forming the weighted supermatrix to consider the interdependency among the elements in the system. At the end, the weighted supermatrix is multiplied by itself until the limit supermatrix is attained in which the final local priorities are reached (Yang et al., 2008).

It is of great importance to consider the computation of the Consistency Ratio (CR) to ensure that expert opinions are not contradicting several aspects in the system. Two parameters are considered in the computation of the CR using equation 4, which are the Consistency Index (CI) and the Random Index (RI). The CI is computed using equation 5.

$$CR = \frac{CI}{Random\ Index} \qquad [4]$$

$$CI = \frac{\lambda - n}{n - 1} \qquad [5]$$

Where λ is the highest eigenvalue in the pairwise comparison matrix and n is the matrix size. However, RI depends on the number of elements in the matrix and is determined using Table 3, adapted from Saaty and Vargas (2002). After determining the two values, the CR is computed accordingly. The pairwise comparison matrix is considered consistent if the CR is < 0.1.

n	1	2	3	4	5	6	7	8	9	10
Random Consistency Index (RI)	0.00	0.00	0.52	0.89	1.11	1.25	1.35	1.40	1.45	1.49

Table 3. Random Consistency Index vs. Elements Number

1. Research Methodology

This study develops a manhole condition assessment model that concludes a condition index for manholes to plan for maintenance and/or rehabilitation. Figure 2 displays the process of the developed model. The model commenced by identifying the possible defects that can emerge in ageing manholes. For example, for the cover and frame and pavements components, protruding services is not considered as a defect, unlike cone and wall components. After filtering the defects for each manhole component, each possessed a unique HOQ; in total, nine models corresponding to nine components are designed. The influence matrix of each HOQ is relevant to the defects involved in each and the values are acquired from the application of DEMATEL. Two questionnaires are designed to obtain the relative influencing and influenced power of the defects and the relative importance weights of the manhole components. The questionnaires are distributed to experts in the field of asset management and mainly sewer experts. Each questionnaire is then analyzed and the sequential DEMATEL and ANP steps are conducted to find the relative weights. Subsequently, the methodology is tested on actual case studies and then validated with mathematical equations.

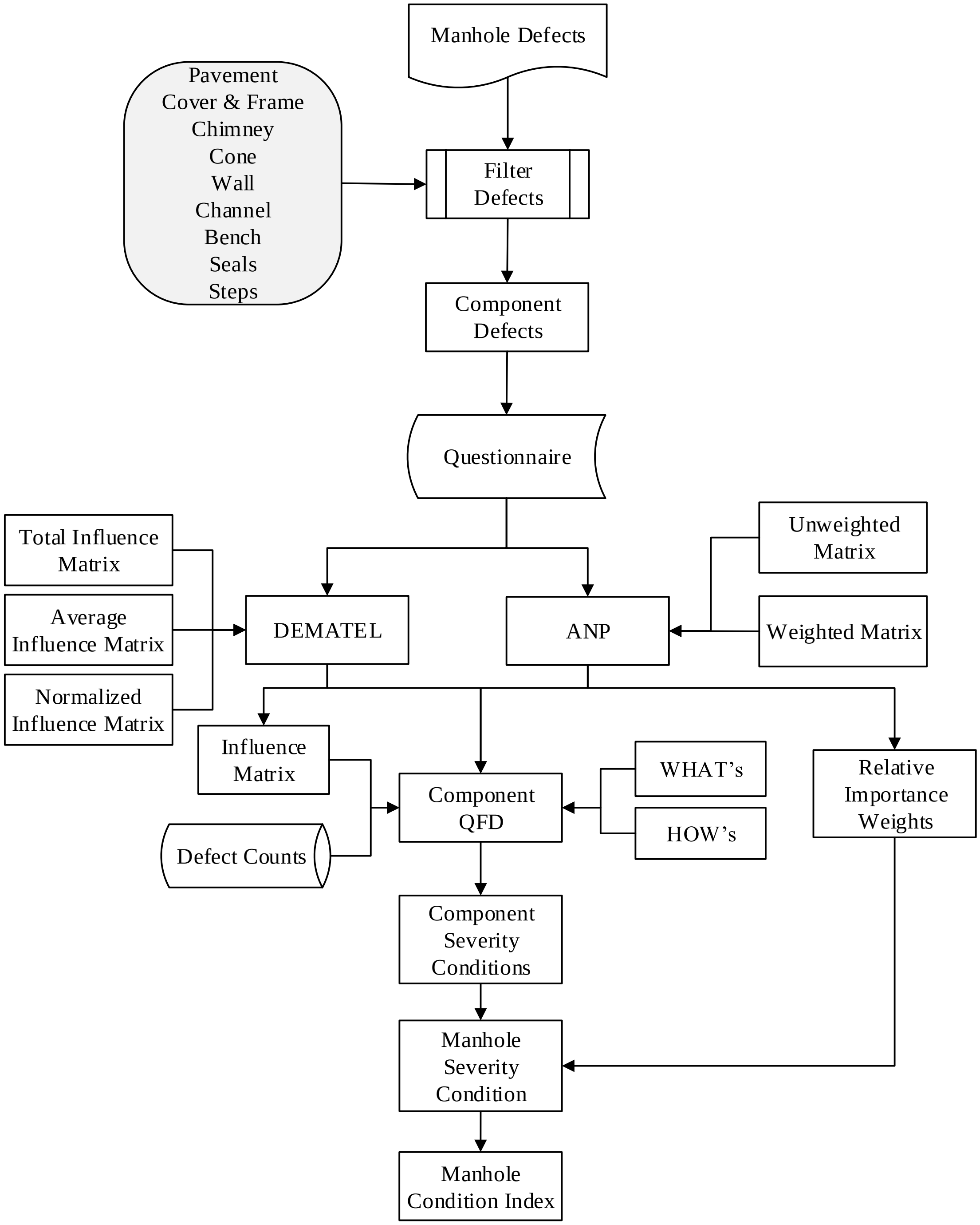


Figure 2. Research Methodology

2. Sewer Manhole Components

The components that are identified and contribute to the overall asset degradation are: pavement, cover and frame, chimney, cone, wall, channel, bench, seals and steps. These components are demonstrated in Figure 3.

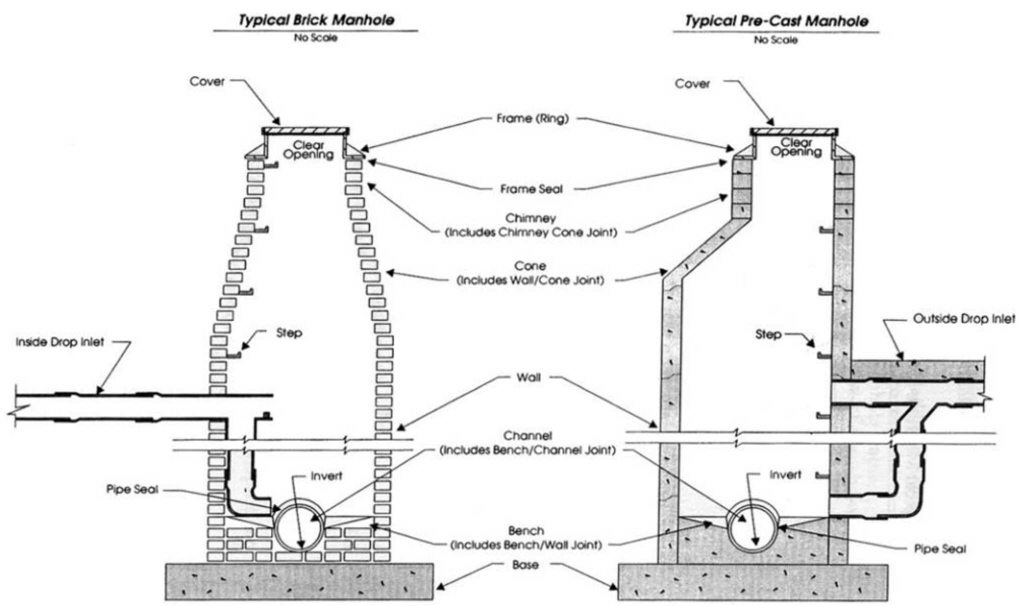


Figure 3. Manhole Components adapted from Hughes [11]

3.1 Pavement

Pavement is the part of the rigid or flexible pavement that is surrounding the manhole cover. It is considered in the manhole assessment as damaged pavements surrounding the asset can expose other components to degrade. According to Hughes (2009), signs of voids outside the manhole structure, which can affect the manhole wall strength, can be triggered from the observations of alligator cracking in asphaltic concrete and spalling, cracking, or tipping in pavements.

3.2 Cover and Frame

Cover is the lid that provides access to the interior of the manhole, while the frame is the cast or ductile ring that supports the cover. Defects identified for these components are cracks, breaks, grades, corrosion and inflow.

3.3 Chimney, Cone and Wall

Chimney is the narrow vertical part build from either brick or concrete materials adjusting rings that extends from the top of the cone to the frame and cover. However, cone is the reduced section that tapers concentrically or eccentrically from the top wall joint to the chimney or the frame and cover. Yet, wall is the vertical barrel portion extending just above the bench joint to the cone. Defects pertinent to these components are vertical cracks, horizontal cracks, vertical fractures, horizontal fractures, deformation, hole, break, collapse, surface damage, roots, I/I, obstruction, attached deposits and protruding services.

3.4 Seals

Materials or devices that prevent intrusion of water at joints of multiple components. Defects pertinent to seals are I/I, cracks and roots.

3.5 Bench

It is the concrete or brick floor of the manhole; generally shaped as a fillet to direct incoming flows to the outlet pipeline and minimize the accumulation of deposits (Hughes, 2009). Defects pertinent to the bench component are vertical cracks and fractures, horizontal cracks and fractures, hole, break, collapse, surface damage, settled deposits, roots and I/I.

3.6 Channel

The flow-shaped way within the bench. Defects pertinent to the channel component are vertical cracks and fractures, horizontal cracks and fractures, multiple cracks and fractures, hole, break, collapse, surface damage, settled deposits, roots, obstruction and I/I.

3.7 Steps

Ladder is made of separated parts that are fixed at multiple components in the manhole. It allows inspectors to move in and out. Defects pertinent to the steps component are related to corrosion, missing and/or broken or missing.

3. Sewer Manhole Defects and Deduct Values

This study assumes several defects in each component depending on its location and the nature of the defects as shown in Table 4. In total eighteen defects are identified and filtered based on the component. According to the table, pavement and steps each have one defect. Chimney, cone and wall share the same defects. Attached deposits are expected to emerge in components above the bench. However, settled deposits are expected to accumulate in the bench and channel.

Defect	Manhole Component								
	Pavement	Cover and Frame	Chimney	Cone	Wall	Seals	Bench	Channel	Steps
Damaged Pavement	●								
Crack (Vertical & Horizontal)		●	●	●	●	●	●	●	
Fractures (Vertical & Horizontal)			●	●	●		●	●	
Break		●	●	●	●		●	●	
Grade		●							
Surface Damage including corrosion		●	●	●	●		●	●	
I/I		●	●	●	●	●	●	●	
Deformation			●	●	●				

Obstruction	●	●	●			●	
Roots	●	●	●	●	●	●	
Attached Deposits	●	●	●				
Collapse	●	●	●		●	●	
Hole	●	●	●		●	●	
Protruding Service	●	●	●				
Settled Deposits					●	●	
Multiple Crack						●	
Multiple Fractures						●	
Damaged, Corroded, Missing Steps							●

Table 4. Manhole Component Defects

Each of these defects have deduct values that were collected from literature (Hughes, 2009; Nelson et al., 2010) and range between 1 and 5, where 1 is excellent and 5 is critical. These values explain the severities of the defect as displayed in Table 5. For example, a component with a deformation of more than 15% is critical and will have deduct value of 5. Nevertheless, a deformation with lower than 2.5% is considered as excellent and a value of 1 is considered.

Defect	Description	Defect Criteria	Deduct Value
Damaged Pavement	Damaged parts of the flexible and rigid pavements surrounding the cover of the manhole	Pavement damage <= 25% of cover circumference	2
		Damage >25% and <=75%	3
		Damage >75%	4
Crack	Any line of crack that are observed in the components. The severity is expressed by the number of cracks recorded	1	1
		2	2
		3	3
		4	4
		>5	5
Break	Any broken parts of the component and expressed by percentage of material loss	>0 and <=2.5%	1
		>0 and <=5%	2
		>5% and <=10%	3
		>10% <=25%	4
		>25%	5

	compared to the actual material area		
Grade	The location of the cover whether it is above, below or on grade	On grade	1
		below or above	5
Corrosion	Any corrosion material observed. It is expressed by the corrosion surface area	>0 and <=2.5%	1
		>0 and <=5%	2
		>5% and <=10%	3
		>10% <=25%	4
		>25%	5
I/I	The inflow of water to the manhole asset through any component	0 and <= 0.757 l/m	1
		>0.757 l/m and <=1.514 l/m	2
		>1.514 l/m and <=3.028 l/m	3
		>3.028 l/m and <=6.057 l/m	4
		>6.057 l/m	5
Deformation	When the cross section of the component is altered horizontally or vertically	Deformation < 2.5%	1
		2.5% and < 5%	2
		5 and <7.5%	3
		7.5 and <15%	4
		>= 15%	5
Surface Damage	Surface is changed from its original condition (loss of wall thickness)	Aggregate visible, cracked mortar	2
		Chipped , wall loss < 10%,eroded mortar	3
		>=10% to <20%, missing brick, missing mortar	4
		>=20%, missing brick	5
Roots	Ingress of roots through defects	<=25% of component	3
		>25% to <=50% of component	4
		>50% of component	5
Attached Deposits	Foreign materials that are attached to the component and continue to accumulate	0-5%	1
		<5%-10%	2
		<10%-20%	3
		<20%-30%	4
		>30%	5

Collapse	Collapse of a component	Collapsed	5
Hole	Visible hole in the component	<=5% of component	1
		>5% and <= 8.33% of component	2
		>8.33% and >= 16.6667 %	3
		>16.667% and <=25%	4
		>25% of component	5
Obstruction	Objects that block parts of the component	0-5%	1
		<5%-10%	2
		<10%-20%	3
		<20%-30%	4
		>30%	5
Protruding Service	Objects that have been inserted after construction	0-5%	1
		<5%-10%	2
		<10%-20%	3
		<20%-30%	4
		>30%	5
Vertical Crack	Line is apparent but not open that is running along the manhole axis	Length <75 mm	1
		75-150 mm	2
		>150-225	3
		>225 - 300 mm	4
		>300 m	5
Horizontal Crack	Line is apparent but not open that is running at right angles to the axis of the manhole	Length <75 mm	1
		75-150 mm	2
		>150-225	3
		>225 - 300 mm	4
		>300 mm	5
Vertical Fracture	An open crack that is running along the manhole axis	Length <75 mm	1
		75-150 mm	2
		>150-225	3
		>225 - 300 mm	4
		>300 mm	5
Horizontal Fracture	An open crack that is running at right angles to the axis of the manhole	Length <75 mm	1
		75-150 mm	2
		>150-225	3
		>225 - 300 mm	4
		>300 mm	5
		0-5%	1

Settled Deposits	Materials settled on the component	<5%-10%	2
		<10%-20%	3
		<20%-30%	4
		>30%	5
Multiple Crack	Combination of vertical and horizontal cracks	Length <75 mm	1
		75-150 mm	2
		>150-225	3
		>225 - 300 mm	4
		>300 mm	5
Multiple Crack	Combination of vertical and horizontal fractures	Length <75 mm	1
		75-150 mm	2
		>150-225	3
		>225 - 300 mm	4
		>300 mm	5

Table 5. Manhole Defects Deduct Values

4. Manhole Overall Condition

The manhole overall condition is computed using the deduct values of each defects observed in each component and the relative weights computed using the DEMATEL and ANP approaches as illustrated in Figure 4. To calculate the overall grade of any component of the manhole, the following equation can be used:

Overall Component Grade (G_{CM}) = $\sum_1^5 RW_i * i$ [6]

where RW is the relative weight of each severity found from aggregating the DEMTAL weights with the HOW's in the each HOQ; i is the weight of each condition severity (i.e. excellent is 1, good is 2, fair is 3, poor is 4 and critical is 5). Later, the relative importance weights of each component are found by the ANP application. The components indexes are then amalgamated to find the overall manhole grade as per equation 7.

Overall Manhole Grade = $\sum_1^9 CW_j * G_j$ [7]

where CW is the relative component weight computed by ANP method and G is the overall grade of each component.

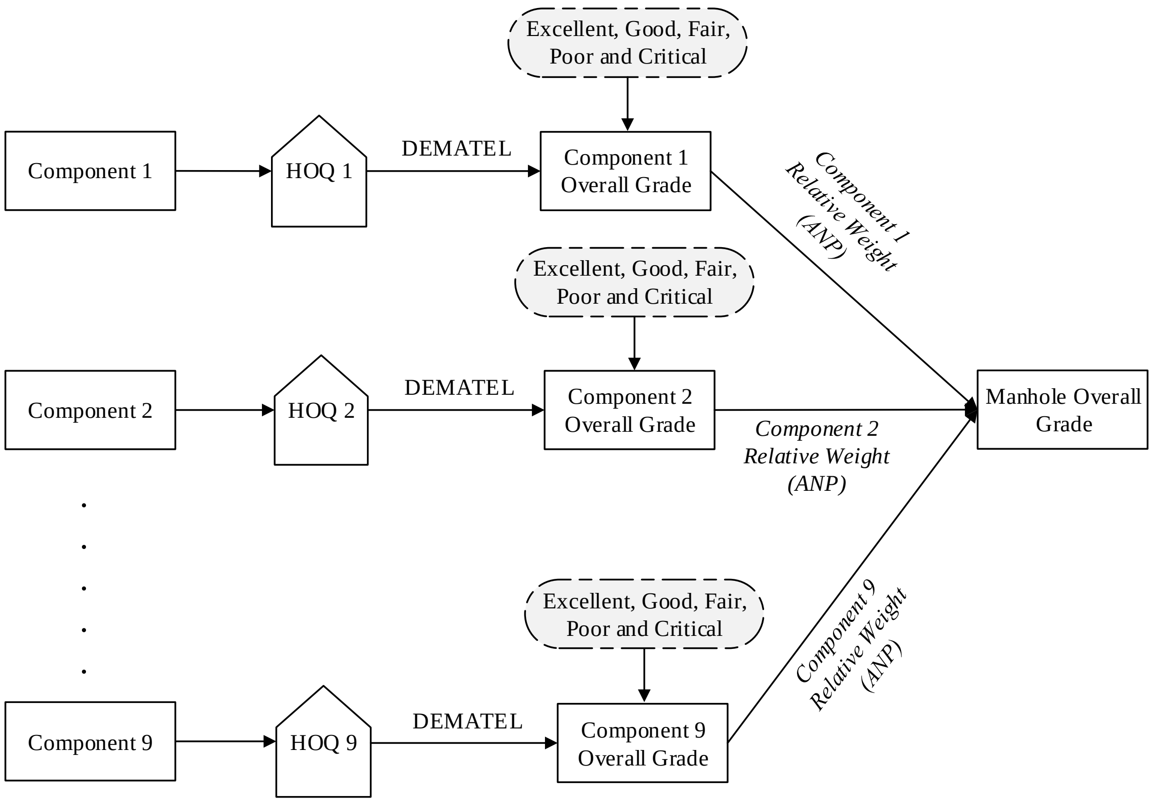


Figure 4. Manhole Components Aggregation Process

In this research, the NASSCO's severities has been adopted in explaining the calculated index (Daher 2015). These classifications and descriptions, shown in Table 6, are essential to distinguish the current conditions of the manholes and has been applied in many researches (Angkasuwansiri and Sinha, 2014; Daher, 2015; Bakry et al., 2016; Kaddoura et al., 2017; Kaddoura and Zayed, 2018). The five classifications, which range between 1 and 5, are excellent, good, fair, poor, and critical.

Overall Manhole Grade	Condition	Description
1.00 to <1.50	Excellent	No to minor defects with small severities
1.50 to < 2.00	Good	Minor defects are observed with small to medium severities
2.00 to < 3.00	Fair	Moderate defects with medium severity
3.00 to <4.00	Poor	Major defects with medium to high severity
4.00 to 5.00	Critical	Severe defects are observed. Manhole/component collapses or collapse is imminent.

Table 6. Proposed Manhole Overall Grades, Conditions and Descriptions

5. Data Collection Analysis

7.1 Participants Information

A questionnaire, pertinent to the application of the DEMTAL and ANP methods, was prepared and distributed to professionals in the field of sewer asset management. The practitioners were sought from different municipalities, consulting companies, and research institutions through their professional and academic profiles found online. About 90% of the 115 questionnaires were sent to professionals and responses received via e-mail, and the remaining were distributed physically as a hard-copy. Fortunately, 28% of the distributed questionnaires were received; specifically, thirty-two experts participated from four different regions: North America (Canada and US), Middle East, Europe and China. The responses that were received from the multiple regions shall provide a generic overview about the influence of the defects and the components importance. The differences in the responses are expected to be minor as this research develops an assessment model that relies on sewer defects and not on physical, operational and environmental factors that could differ from one region to another.

The respondents' years of experience varied as displayed in Table 7. As shown in the table, the highest number of responses was from the participants with experience between 9 and 15 years. However, the lowest number of the responses was from the participants with experience between 3 and 6 years. Besides, the participants from North America responded the most when compared to the other areas; while the Middle East region's respondents were the lowest participants. This was expected, since the practices of sewer condition assessment and trenchless technology are not as popular in the Middle East when compared to the other regions.

Years of Experience	Responses
1-3 years	6
3 - 6 years	4
6 - 9 years	7
9 - 15 years	9
15+ years	6
Total	**32**

Table 7. Respondents Years of Experience

7.2 HOQ Influence Matrix Questionnaire

This questionnaire was pertinent to the deployment of the DEMATEL method in finding the influence power between the elements in the system. Each table, in Figure 5, represents two different defects. The expert shall select the influence of X on Y and the influence of Y on X considering the 0, 1, 2, 3, and 4 factors. As a result, the experts could decide the bidirectional influence power between any two defects. For instance, if a participant believes fractures have higher influence power on I/I, the participant will choose 4 in the X to the Y direction.

X	No Influence	Low Influence	Medium Influence	Extreme Influence	High Influence	Y
Deformation	0	1	2	3	4	Crack
	4	3	2	1	0	
X	High Influence	Extreme Influence	Medium Influence	Low Influence	No Influence	Y

X	No Influence	Low Influence	Medium Influence	Extreme Influence	High Influence	Y
Fracture	0	1	2	3	4	Infiltration
	4	3	2	1	0	
X	High Influence	Extreme Influence	Medium Influence	Low Influence	No Influence	Y

X	No Influence	Low Influence	Medium Influence	Extreme Influence	High Influence	Y
Roots	0	1	2	3	4	Infiltration
	4	3	2	1	0	
X	High Influence	Extreme Influence	Medium Influence	Low Influence	No Influence	Y

Figure 5. HOQ Influence Questionnaire Sample

A step by step calculation of the cause and effect defects for the cover and frame components will be discussed. Similar steps are followed for constructing the HOQs of the other components.

a) The influence matrix, shown in Figure 6, is constructed after considering the average value of each respondent. Considering the relation between cracks and inflow, the influence of cracks on inflow is 3.91, however, the influence of inflow on cracks is 0.64. According to the experts, cracks have extreme influence on causing inflow but lower low influence in the opposite direction.

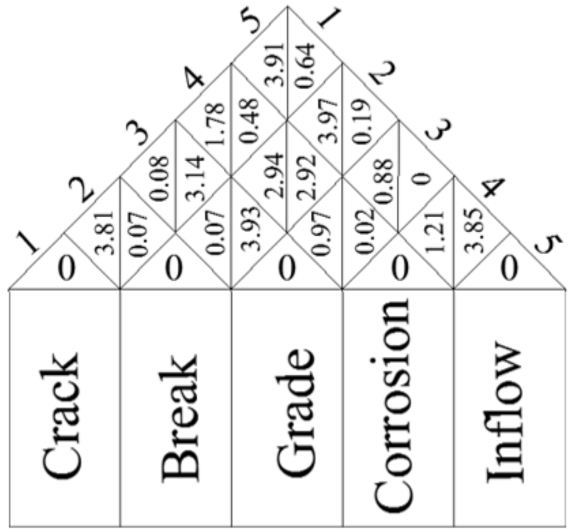


Figure 6. Cover and Frame Influence Matrix

b) The normalized influence matrix is calculated after summing the columns and rows for each defect when arranging the average influence values in a matrix form. The maximum value of the aforementioned result is used to form the normalized matrix as per Table 8.

Defect Number	1	2	3	4	5
1	0	0.35	0.01	0.16	0.36
2	0.01	0	0.01	0.27	0.37
3	0.29	0.36	0	0.09	0.08
4	0.04	0.27	0	0	0.11
5	0.06	0.02	0	0.35	0

Table 8. Cover & Frame Normalized Influence Matrix

c) Total Average Matrix

The total average matrix, shown in Table 9, is the final major computation of the DEMATEL approach. From the resulting matrix, one can determine the influencing power of each defect after evaluating C+R, which is displayed in Table 10. According to the table, the highest influencing power is the corrosion (23.14%). However, the least influencing power is the grade (14.51%). In addition, R-C categorizes the defects in the system as influencing or influenced defect. Any value that is less than zero is categorized as influenced defect "effect", however, any value that is more than zero describes an influencing defect "cause". In this HOQ, there are two influencing defects: cracks and grade; however, there are three influenced defects: break, corrosion and inflow. As a result, 40% of the system is based on influenced defects and 60% is based on influencing defects.

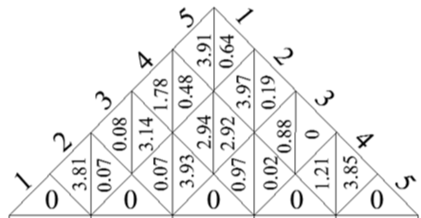
Defect Number	1	2	3	4	5
1	0.07	0.54	0.01	0.55	0.65
2	0.06	0.17	0.01	0.51	0.51
3	0.35	0.63	0.01	0.49	0.49
4	0.07	0.36	0.01	0.21	0.29
5	0.09	0.18	0	0.47	0.15

Table 9. Cover & Frame Total Average Matrix

Number	Rows (R)	Columns (C)	C+R	R-C	Weight
1	1.82	0.64	2.46	1.175115	17.88%
2	1.26	1.88	3.14	-0.61865	22.78%
3	1.96	0.04	2.00	1.926171	14.51%
4	0.95	2.24	3.19	-1.28927	23.14%
5	0.90	2.09	2.99	-1.19336	21.69%

Table 10. Cover & Frame DEMATEL Results-Weights, Influencing and Influenced Defects

As a result, the complete HOQ of the cover and frame is displayed in Figure 7. The figure shows the relationship matrix as well as the severity conditions ranging from 1 to 5. In addition, the HOW's represent the defect counts observed in this component using the reports.



		2.46	3.14	2.00	3.19	2.99
		Crack	Break	Grade	Corrosion	Inflow
Condition	**Defect Number**	1	2	3	4	5
	Score/Weight	17.88%	22.78%	14.51%	23.14%	21.69%
Excellent	1	0.00%	100.00%	100.00%	50.00%	0.00%
Good	2	100.00%	0.00%	0.00%	0.00%	0.00%
Fair	3	0.00%	0.00%	0.00%	0.00%	0.00%
Poor	4	0.00%	0.00%	0.00%	50.00%	0.00%
Critical	5	0.00%	0.00%	0.00%	0.00%	0.00%
Excellent	1	0	1	1	1	0
Good	2	1	0	0	0	0
Fair	3	0	0	0	0	0
Poor	4	0	0	0	1	0
Critical	5	0	0	0	0	0

Figure 7. Cover and Frame HOQ

Hence, the results of the DEMATEL deployment for the rest of the components are shown in Figures 8-11. The figures display the weights of each defect in each component as well as the R-C values. In addition, Table 9 provides the summary of the results by stating the highest and lowest defects weights in each component as well as the overall cause and effect defects in each component. Based on the results, most of the assets have higher influencing defect percentages except for the seals' manhole component. This is due to the fact that the defects that are defined for this component are crack, roots and inflow/infiltration. Based on these defects, it is obvious that a crack or a deterioration in the seals lead to the root penetration and/or I/I. However, other assets and components involved higher number of influencing defects based on experts' opinions. Also, root defect emerged as a significant defect that has a great influence power in multiple components in the manhole.

According to Schrock (1994), roots can expand an existing opening in a sewer causing weakening in the structure and ultimately leading to breakage and collapse. Hence, the accumulated effect of the root intrusion on other defects resulted in higher influence power compared to other defects. On the other hand, the repeated lowest influence defect found in multiple parts is the protruding services. Protruding services present in the sewer system due to construction and design faults and do not exist due to a cause of other sewer defects. Therefore, the accumulation of influence power was restrained resulting in smaller weight.

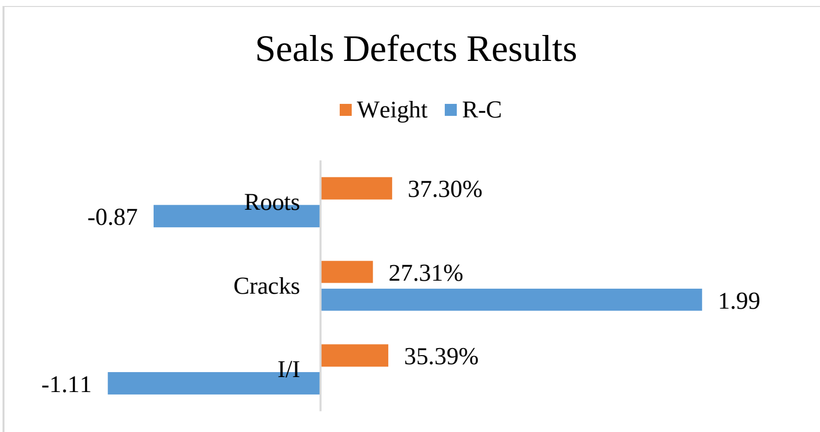


Figure 8. Seals Defects DEMATEL Results

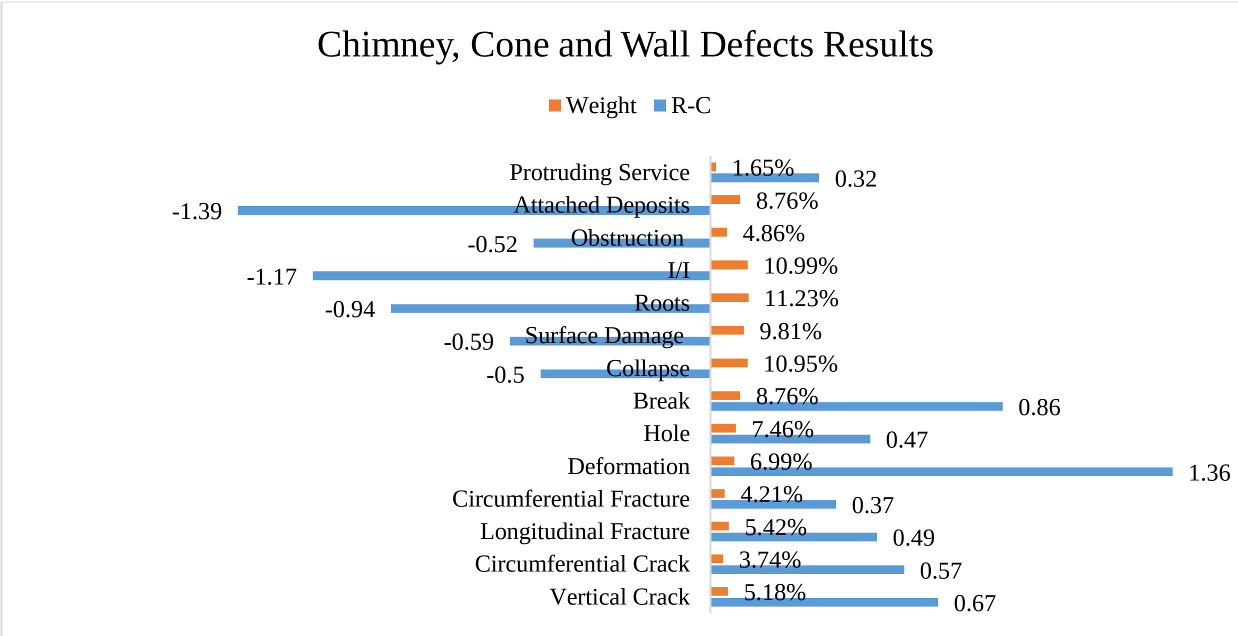


Figure 9. Chimney, Cone and Wall Defects DEMATEL Results

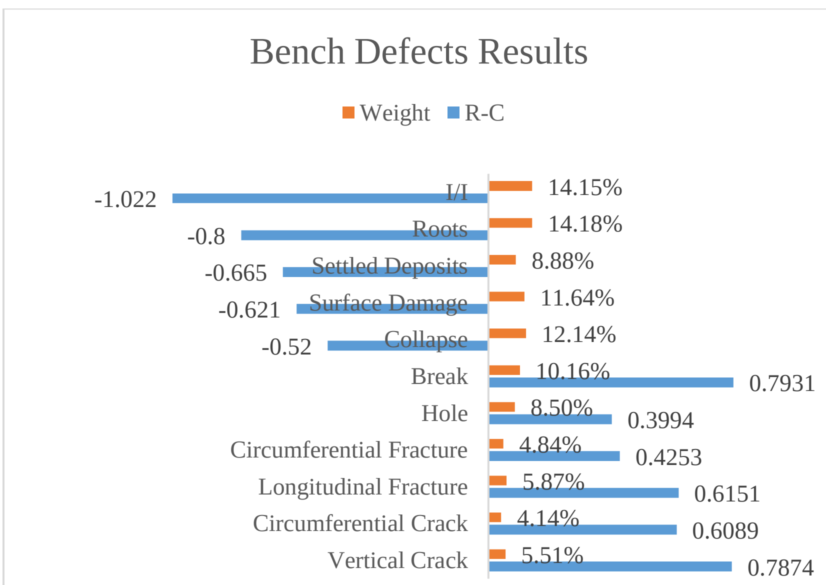


Figure 10. Bench Defects DEMATEL Results

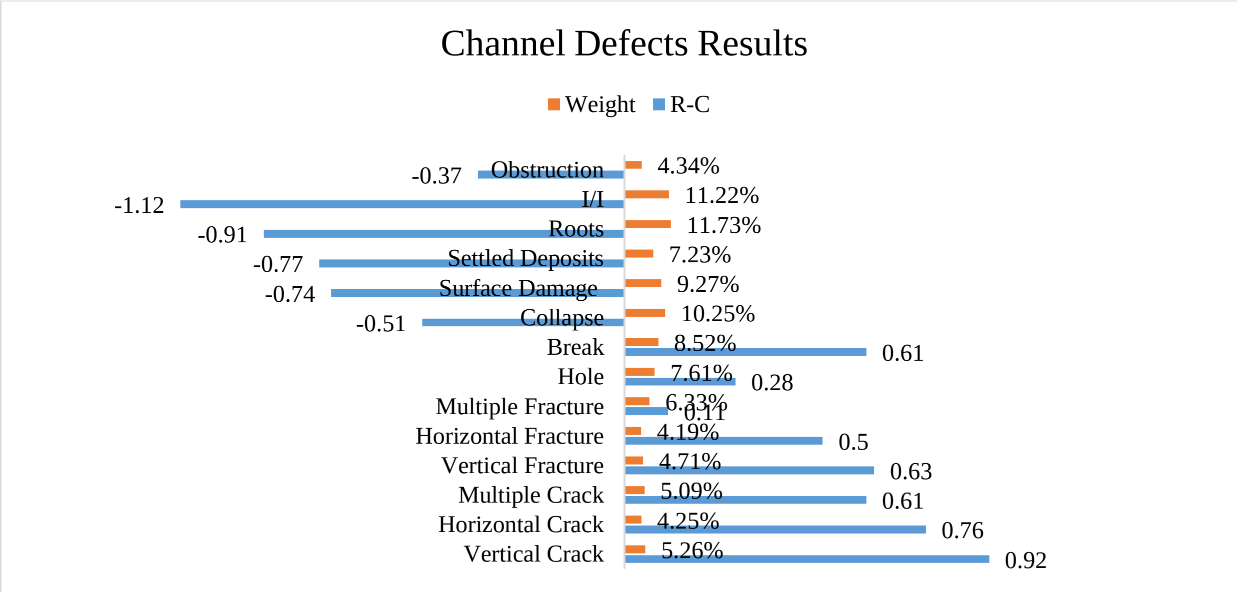


Figure 11. Channel Defects DEMATEL Results

Component	Highest Influence Power	Lowest Influence Power	Influencing %	Influenced %
Cover & Frame	Corrosion	Grade	60	40
Seals	Roots	Cracks	33	67
Chimney	Roots	Protruding services	57	43
Cone	Roots	Protruding services	57	43
Wall	Roots	Protruding services	57	43
Bench	Roots	Horizontal Crack	55	45
Channel	Roots	Circumferential Fracture	57	43

Table 11. Summary of DEMATEL Approach

7.3 ANP Questionnaire

Figure 12 shows a screenshot of the same questionnaire that was sent to the experts. The respondents filled the questionnaire by comparing component X and Y with respect to Z.

Degree Of Importance										
X	(9) Absolute	(7) Very Strong	(5) Strong	(3) Moderate	(1) Equal	(3) Moderate	(5) Strong	(7) Very Strong	(9) Absolute	Y
(Z) Cone										
										Pavement
										Chimney
										Wall
Cover										Steps
										Seals
										Channel
										Bench
(Z) Cover										
										Pavement
										Cone
										Wall
Chimney										Steps
										Seals
										Channel
										Bench
(Z) Seals										
										Pavement
										Cone
										Wall
Channel										Steps
										Cover
										Chimney
										Bench
(Z) Pavement										
										Seals
										Cone
										Pavement
Wall										Steps
										Cover
										Channel
										Bench

Figure 12. Sample of Manhole Relative Importance Questionnaire

The results of the ANP deployment are shown in Figure13. According to the experts, the highest components' weights are walls, cone, cover and frame and seals with few percentages difference. However, the least weights are for pavement and steps component. Therefore, they have minimal contribution to the overall manhole condition.

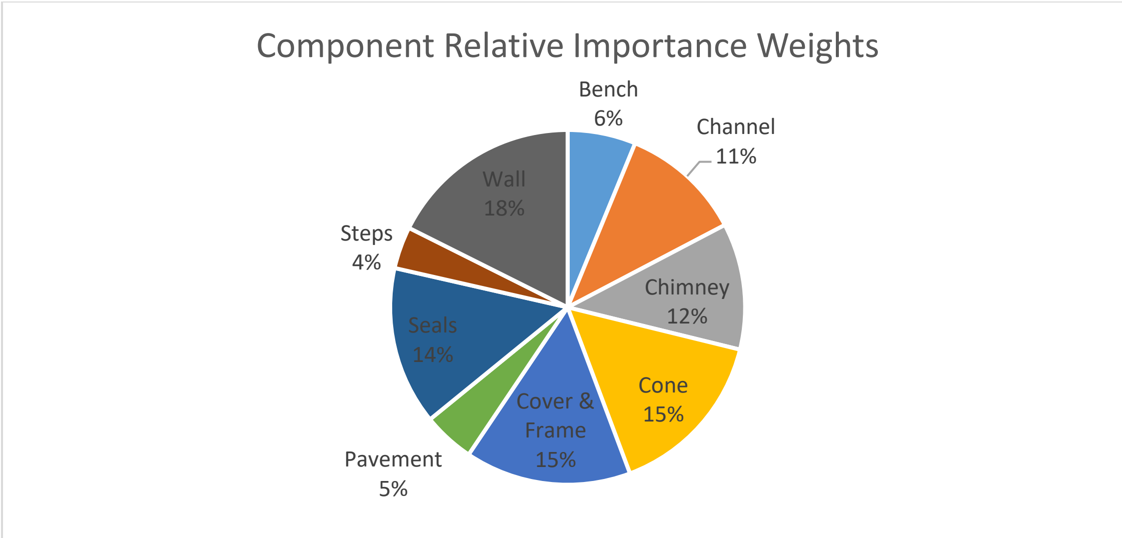


Figure 13. Manhole Components Weights

7.4 Case Study

This research obtained twenty-four manhole from the Royal Gardens' sewer network located in the city of Edmonton. The city provided ".ipf" format files for manholes. PipeTech View software was used to run the manhole inspection files. A 360 degree view of each manhole was acquired with the help of the software; zoom in and out as well as pan and tilt views were accessible. In this context, 24 extensive manhole reports were supplied by the city. Due to the scarcity of the overall manhole conditions, the reports were re-evaluated by an expert as shown in Table 12. For validation purposes, these conditions will be considered as actual values.

Manhole #	Condition	Manhole #	Condition	Manhole #	Condition
1	3	9	4	17	2
2	4	10	4	18	1
3	3	11	2	19	2
4	3	12	2	20	3

Manhole #	Condition	Manhole #	Condition	Manhole #	Condition
5	3	13	4	21	2
6	2	14	2	22	3
7	2	15	3	23	2
8	4	16	2	24	3

Table 12. Manholes Actual Conditions

6. Model Implementation & Validation

8.1 Model Implementation

The defects in each manhole in the case study was reviewed and the defect counts were recorded in each condition severity in the HOQ of each component and based on the deduct values of each defect. According to Table 13, the condition of each component was computed and later all the indexes were aggregated to find the overall condition of the manhole. To better represent the overall grades and their corresponding condition category, Figure 14 is displayed. Based on the figure, 4% of the manholes are rated as poor; however, 54% of the manholes are rated as fair; yet, 34% of the manholes are in good condition. Nevertheless, 8% of the manholes are in excellent condition. According to the assessment, no critical condition is depicted.

Manhole	Overall Component Grade									Manhole Overall Grade	Actual
	Pavement	Cover & Frame	Seals	Chimney	Cone	Wall	Bench	Channel	Steps		
1	1	1.67	1.27	2.08	2	2.04	2.07	2.71	2.63	1.92	3
2	1	2.41	1.27	2.56	3.14	3.51	2.92	3.78	3.54	2.73	4
3	4	2.2	1	1.74	3.69	2.94	3.26	2.71	3.46	2.59	3
4	2	2.26	1.18	2.29	3.39	2.5	3.4	2.89	3.29	2.49	3

5	5	1.55	1.28	3.04	2.2	2.22	3.07	2.61	2.79	2.33	3
6	3	2.32	1.28	3.27	2.45	2.38	3.11	2.41	2.67	2.41	2
7	3	2.95	1.18	3.42	2.47	2.47	3.49	2.31	3.1	2.56	2
8	5	2.84	1	3.71	2.64	2.74	4.15	4.1	3.44	2.97	4
9	5	3.63	1.27	4.21	2.49	2.55	4.23	4.3	3.57	3.16	4
10	1	1.69	1.31	2.57	2.1	2.13	3.58	4.12	2.67	2.27	4
11	1	2	1	2.2	2.47	2.31	2.45	1.87	2.44	1.99	2
12	3	2.31	1	3.64	1.74	2.44	3.18	3.41	2.81	2.44	2
13	1	1.41	1.12	3.17	1.86	3.37	3.74	3.89	3.12	2.45	4
14	2	1.65	1	1.85	1.1	3.56	3.4	3.47	3.12	2.21	2
15	1	1	1	3.12	1.21	2.05	2.16	2.25	3	1.75	3
16	1	1	1	3.59	1.13	1.97	2.03	2.04	2.51	1.73	2
17	1	1.21	1	2.95	1.37	2.97	2.52	2.69	2.19	1.99	2
18	3	1.12	1	1.31	1.03	1.45	2.03	1.21	2.1	1.36	1
19	5	1.34	2.34	3.67	1.56	2.59	2.34	1.67	3.12	2.35	2
20	2	1	1	3.86	1.21	1.69	2.17	2.36	3.1	1.83	3
21	1	1	1	1.23	1.19	1.13	3.22	2.41	3.21	1.46	2
22	2	1.12	1	3.54	2.15	3.64	1.32	1.54	3.19	2.16	3
23	5	1	1	3.66	1.18	1.14	2.68	2.96	3.28	1.96	2
24	1	1	1	3.58	1.51	2.64	2.19	2.51	3.21	1.99	3

Table 13. Royal Gardens Manhole Conditions

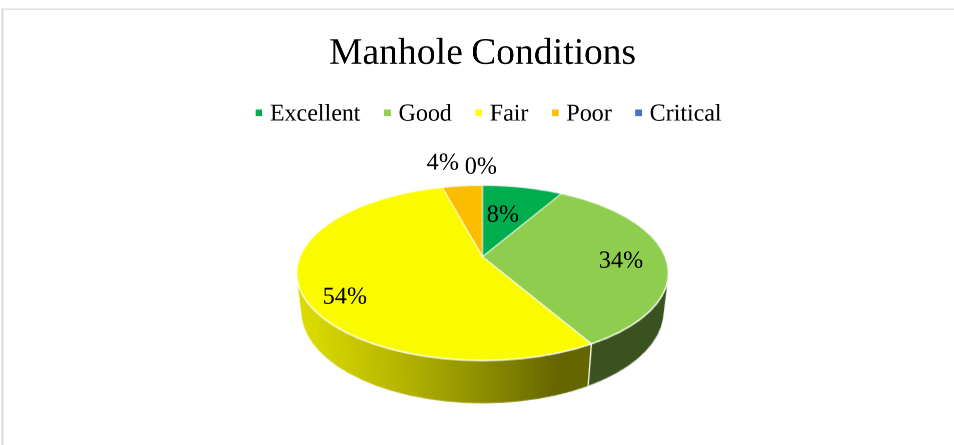


Figure 14. Royal Gardens Manholes Conditions Categories

8.2 Model Validation

The manhole condition assessment model are validated with the actual values obtained from an expert. Five different mathematical validation equations are used. Equations 8 and 9 show the average invalidity percentage (AIP) and the average validity percentage (AVP) in order to check the accuracy of the estimated overall grade. The more the AIP is closer to 0.00, the model is sound. In addition, the root mean square error (RMSE) and the mean absolute error (MAE) are estimated according to equations 10 and 11, respectively. If their values are close 0, the model is precise and vice versa. Considering the validation equations, the AVP is calculated as 76.24%, RMSE is 0.84, and MAE is 0.69. The results suggested that there are deviations from the actual values. This is expected as the expert values are based on first guess and more influenced by the severest defect observed in the manhole regardless of its location.

7. Conclusions

It is of great necessity to preserve the sewer infrastructure to avoid any collapse of sewer assets. This study established a comprehensive manhole assessment that is based on the application of an integrated QFD and DEMATEL approaches as well as the ANP technique. The component-and defect-based model divided the manhole to nine different components and identified number of defects that could be observed in each of them. This paper investigated the cause and effect relationship between the defects in each component and categorized the influencing and influenced defects. Most of the divided components possessed higher percentages of influencing defects and the most repeated highest relative influence weight was the root defect. Nevertheless, the lowest influence power weight was for the protruding services. In addition, this study concluded that walls, cone, cover and frame and seals components are important elements in computing the overall grade of the manhole. The model validation confirmed deviations compared to actual values as the RMSE and AVP were 0.84 and 76.24%, respectively. Nevertheless, the sequential process is expected to provide more solid results than the current practices and expert guesses. According to the model, on average, the overall condition model is based on 53.7% influencing defects and 46.3% influenced defects. Hence, fixing the influencing defects can save more than 45% of the total rehabilitation costs.

This model can be further enhanced if additional defects are added to the model that can be observed in rehabilitated manholes. Additionally, the consistency of the responses of the DEMATEL approach need be further investigated to attain sound results. Besides, it is recommended that each response, in the DEMATEL questionnaire, be analyzed separately instead of considering the average of the influence responses. Further, the developed model can accompany risk assessment, decision support rehabilitation plan, and scheduling models in an automated tool to facilitate the management of sewer manholes. This will expedite the assessment, prioritization, and intervention decisions of the assets.

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