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Quality Function Deployment Application in Sewer Pipeline Assessment

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***Abstract*—**Infrastructure assets are essential in urban cities; their purpose is to facilitate the public needs. As a result, their conditions and states shall always be monitored to avoid any sudden malfunction. Sewer systems, one of the assets, are an essential part of the underground infrastructure as they transfer sewer medium to designated areas. However, their conditions are subject to deterioration due to ageing. Therefore, it is of great significance to assess the conditions of pipelines to avoid sudden collapses. Current practices of sewer pipeline assessment rely on industrial protocols that consider distinct defects and grades to conclude the limited average or peak score of the assessed assets. This research aims to enhance the evaluation by integrating the Quality Function Deployment (QFD) and the Decision-Making Trial and Evaluation Laboratory (DEMATEL) methods in assessing the condition of sewer pipelines. The methodology shall study the cause and effect relationship of the systems' defects to deduce the relative influence weights of each defect. Subsequently, the overall grade is calculated by aggregating the WHAT's and HOW's of the House of Quality (HOQ) using the computed relative weights. Thus, this study shall enhance the evaluation of the assets to conclude informative rehabilitation and maintenance plans for decision makers.

***Keywords*—**Condition assessment, DEMATEL, QFD, sewer pipelines.

I. Introduction

ASSESSING the condition of infrastructure assets is essential due to its backbone need for any urban city [1]. Sewer systems, forming one of the most capital-intensive infrastructure systems [2], transfer sewage medium from private/public outlets (i.e. buildings, houses, hospitals, schools, etc.) to laterals, which are connected to main pipelines that end at a sewage treatment plant or a disposal area. However, they are the ultimate low-profile infrastructure assets in spite of their health and environmental benefits [3]. These systems are buried in the subsurface and are distributed in a maze of a complex infrastructure. Their low visibility stands a reason for their low frequent rehabilitation and/or maintenance [2]. As a result, they are prone to collapse and failure, imposing severe consequences on the surroundings [3] and resulting in costly and difficult rehabilitation [2]. Therefore, studying the performance of the system is essential to gain knowledge about the future conditions of the sewer assets for rehabilitation purposes [4] and budget allocation. The necessity of this task is deduced from the reinforcing loop shown in Fig. 1. The higher is the condition of an asset provides a higher overall performance of the system (reinforcing relationship). The higher is the overall performance requires less rehabilitation and maintenance (balancing relationship). Therefore, the costs for rehabilitation and maintenance are less (reinforcing relationship). Furthermore, funds will be available to enhance other assets' performance and hence the overall sewer system's performance (reinforcing relationship).

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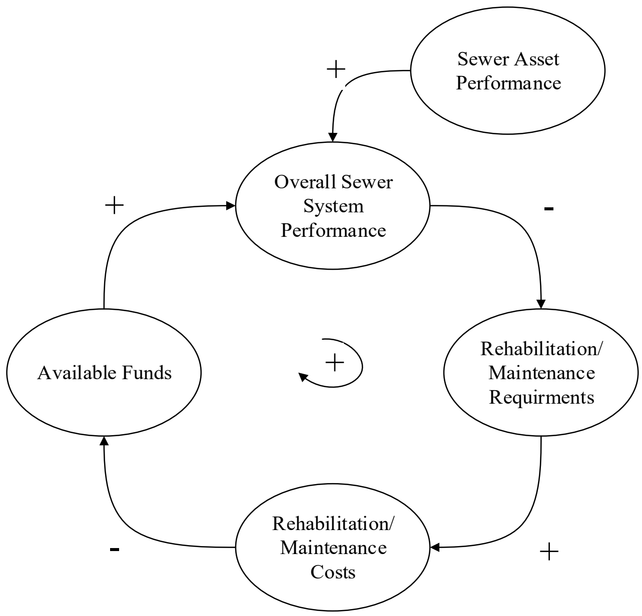

Fig. 1 Reinforcing loop

Several countries are publishing infrastructure report cards to inform the government about the condition of their infrastructure assets. In Canada, for example, [5] claimed a Very Good overall rating for the linear wastewater system. However, due to ageing, these assets are subject to deterioration over time. This can be triggered from Table I, which displays a history glance of the wastewater system condition in the United States based on the American Society of Civil Engineers (ASCE). Since 1988, the US wastewater condition is deteriorating in spite of grades improvements in some years due to rehabilitation/replacement practices.

Current practices rely on the Closed Circuit Television (CCTV), the widely used inspection technique, in recording the inner condition of the pipeline. After that, an overall rating is deduced based on a specific standard in which each municipality uses. The overall rating is concluded using either the peak score or the mean score of all defect grades. Peak scores flatten the data and provide vague overall rating for the pipeline [6] as some defects are neglected. However, the overall grading deduced from the mean calculation considers common weights for all the defects, which results in misleading conclusions for the decision makers.

Some efforts in the literature have been made to enhance the current practices. For example, reference [7] developed a performance index model for sewer pipelines that was based on the structural and operational indexes. The authors suggested four modules in each. In calculating the structural index, the authors used the external corrosion, internal corrosion, surface wear and load modules. However, in computing the operational index, the authors considered the infiltration/exfiltration, blockage, root penetration and hydraulic modules. The researchers used the fuzzy expert system and the weighted method in supplying the indexes. In spite of the efforts, the inputs required in the methodology require extensive information that could be missing in many municipalities. Also, reference [6] relied on the defects detected to conclude a condition index for sewer pipelines. The author deployed fuzzy expert system, Analytic Network Process (ANP) and the Hierarchal Evidential Reasoning (HER) in the evaluation. However, one significant defect was missing, as other protocols, which is the void erosion. Similarly, reference [8] proposed a model that is based on the multi attribute utility to assess the condition of the sewer pipelines based on four different defects: deformation, surface damage, settled deposits and infiltration. The approach relied on inspection technologies other than CCTV as inputs to the model. However, the suggested model did not include many of the defects that could be detected in sewers.

In fact, some authors relied on other techniques to predict the condition of sewer pipelines using different type of techniques such as Artificial Neural Network (ANN) [9], [10], Support Vector Machines (SVMs) [11], simulation models [12], multiple regression [13]-[15], etc. However, many of the prediction models require input data that are related to sewer characteristics such as slope, diameter, location, sewer type, etc. Nevertheless, such data need accessible database from municipalities.

TABLE I
ASCE WASTEWATER GRADES

Year	Wastewater Grade	
1988	C	[16]
1998	D+	[17]
2001	D	[18]
2003	D	[19]
2004	D	[20]
2005	D-	[21]
2009	D-	[22]
2013	D	[23]
2017	D+	[24]

This study shall focus on assessing sewer pipelines by integrating the QFD and the DEMATEL methods to calculate the overall condition of the buried assets. The proposed methodology is an alternative enhanced evaluation method that is expected to amplify the current evaluation of sewer pipeline assessment after studying the cause and effect relationship between the defects involved. Therefore, decision-makers are able to allocate budgets for maintenance/ rehabilitation actions.

II. RESEARCH TECHNIQUES

A. Quality Function Deployment (QFD)

QFD is a technique that is utilized to convert customer needs into technical requirements in each stage of the product development. It is conducted to attain several quality issues' objectives [25]:

1. Improve quality of design
2. Provide planned quality control chart before the initial production run

The method was firstly developed in Japan in 1966 by Yoji Akao; nevertheless, the approach was not formalized in quality control planning until 1972 [26]. Since then, QFD approach was rapidly spread across Japan and the US [26]. 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 [27]. It focuses on implementing the voice of the customer, a critical step, after assessing their needs, which are usually determined by interviews and/or focus groups or surveys, to ensure their satisfaction [27].

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 [28]. After that, the absolute weights are determined by aggregating the HOW's and the WHAT's through the use of the factors in the matrix established earlier. Consequently, the HOQ is then finalized; a basic representation is depicted in Fig. 2.

The aforementioned method is proposed as an alternative approach to be used in the condition assessment of the sewer pipelines. As a result, the method will be restructured to suit its application in infrastructure condition assessment. Thus, in the context of this research, each component is considered as follows:

- WHAT's are the condition severity. Herein, five different severities are considered: Excellent, Good, Fair, Poor and Critical. These severities conclude the asset condition.
- HOW's represent the defects considered in each asset under assessment in percentagewise.
- Relationship matrix is the 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. In this research, five different grades are considered.
- HOQ represents the complete application of the QFD in a diagram as in Fig. 2.

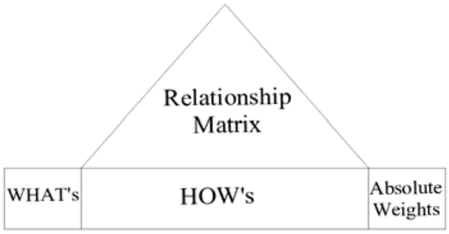

Fig. 2 HOQ general representation

B. Decision-Making Trial Evaluation Laboratory (DEMATEL)

Decision-Making Trial Evaluation Laboratory (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 [29]. DEMATEL approach could improve understanding a specific "problematique" for a cluster of intertwined problems and contribute to the identification of workable solutions by a hierarchical structure [29]. This method is capable of establishing an interdependency relationship between the participating variables in a cause and effect concept to conclude the causing and effected variables [29]. 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. Suppose that there are four elements in the system, then the influence matrix is represented as per Fig. 3. Taking element 2 and 3 as an illustration, a_{23} is the influence of element 2 on element 3. However, a_{32} is the influence of element 3 on element 2. In fact, the zeros in the triangle are the diagonal values of the matrix which are always zeros. The influence is represented by 0, 1, 2, 3 and 4 that indicates "no influence", "low influence", "medium influence", "high influence" and "extreme influence", respectively. 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. Subsequently, causing and affected elements are categorized.

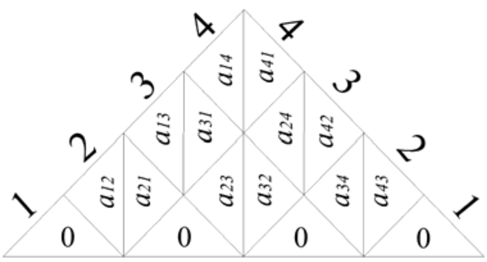

Fig. 3 Influence matrix in HOQ

III. Research Methodology

This research integrates the QFD and DEMATEL approaches in evaluating sewer pipelines as per Fig. 4. It is understood that sewer defects have a cause and effect relationship. For example, reference [30] stated that void erosion can cause deformation in which the latter could be a reason for some cracks. This is due to the evolving nature of one defect to another (i.e. excessive deformation can change cracks to fractures). This relationship is constructed and deduced from a questionnaire that is prepared and sent to experts in the field. The responses shall conclude the relationship factors among the defects after calculating the average influence matrix, normalized influence matrix and the total influence matrix. In addition, the WHAT's in the QFD model represents the severity levels that are considered. In this research, five different severity conditions are adopted: Excellent "1", Good "2", Fair "3", Poor "4" and Critical "5". On the other hand, the HOW's of the QFD model are the percentages of defects, which are found from the inspection reports, in each severity level. Subsequently, the aggregation of each severity level is accomplished by considering the weights from the DEMATEL approach. Finally, the condition index of the pipeline is calculated after using the weights of each severity.

IV. Pipeline Condition Assessment Model

Pipeline condition assessment in infrastructure asset is an important practice as it helps decision-makers to plan for rehabilitation and/or maintenance as well as for budget allocation. It signifies whether decisions makers shall react immediately or not. In fact, it encourages proactive maintenance rather than the expensive reactive maintenance. As a result, infrastructure authorities can take actions to prevent pipelines from collapse scenarios.

The first step is gathering defects that affect the condition of the pipeline. In addition to the common defects discussed in many available protocols, soil loss known as void erosion, is added to the model as listed in Table II. This defect is considered due to its extreme importance in causing other defects as stated by reference [30]. Therefore, the HOW's of the QFD model are made up of 22 elements as per the same table. The HOW's are found from the inspection reports that categorize the defects and the severities. Based on the defect counts, the percentages are calculated for each defect. Similar process is accomplished for the other defects, if detected. Once the HOW's are calculated, the defects are aggregated in each severity condition based on the weights found from the causality relationship between the elements as shown in Table III. Therefore, a matrix of r = 5 and c = 22 is formed. In order to study the causality of the elements in the model, DEMATEL approach is utilized. To do so, a designed questionnaire was sent to sewer experts in different regions to fill the influence of one defect to the other. Therefore, an average influence matrix can be established and used in the HOQ instead of the regular correlation matrix. Based on the DEMATEL and QFD integration, severity percentages are calculated after aggregating each severity percentage of each defect together following (1). The overall grade of the pipeline is found by aggregating the grades percentages with the value of the grade condition as per (2).

TABLE II
SEWER PIPELINE DEFECTS

Number	Pipeline Defects	Description
1	Longitudinal Crack	Line is apparent but not open that is running along the pipeline axis
2	Circumferential Crack	Line is apparent but not open that is running at right angles to the axis of the pipeline
3	Multiple Crack	Combination of longitudinal and circumferential cracks
4	Longitudinal Fracture	An open crack that is running along the pipeline axis
5	Circumferential Fracture	An open crack that is running at right angles to the axis of the pipeline
6	Multiple Fracture	Combination of longitudinal and circumferential fractures
7	Deformation	When the cross section of the pipeline is altered horizontally or vertically
8	Hole	A visible hole in the pipeline
9	Break	Pieces are noticeably displaced in the pipeline wall
10	Sag	When pipeline slope changes; it can be detected through ponds.
11	Collapse	Loss of structural integrity of the pipeline
12	Surface Damage	Pipeline surface is changed from its original condition (loss of wall thickness)
13	Settled Deposits	Materials in a sewer pipeline which could cause flow turbulence and reduction of cross section (i.e. debris)
14	Soil Deposits	presence of soil from pipeline inlets or surrounding ground; causing turbulence in the flow
15	Roots	Ingress of roots through defects
16	Infiltration	Ingress of groundwater through defects
17	Obstruction	An obstacle in the drain
18	Offset Joint	A pipe is not concentric with the socket of the adjacent pipe
19	Open Joint	Adjacent pipelines which are longitudinally displaced at the joint
20	Soil Loss	Loss of soil support around the pipeline
21	Attached Deposits	Foreign materials that are attached to the sewer pipeline and continue to accumulate
22	Protruding Service	Objects that have inserted after construction

TABLE III
WHAT'S & HOW'S REPRESENTATION

W_c	Weight	W_1	W_2	W_3	…	W_{22}
WHAT's		1	2	3	…	22
SC_{1c}	Excellent	SC_{11}	SC_{12}	SC_{13}	…	SC_{122}
SC_{2c}	Good	SC_{21}	SC_{22}	SC_{23}	…	$SC2_{22}$
SC_{3c}	Fair	SC_{31}	SC_{32}	SC_{33}	…	SC_{322}
SC_{4c}	Poor	SC_{41}	SC_{42}	SC_{43}	…	SC_{422}
SC_{5c}	Critical	SC_{51}	SC_{52}	SC_{53}	…	SC_{522}

$$SCr = \sum_{c=1}^{22} SCrc * Wc \quad (1)$$

where W is the weight of each defect; SC is the severity condition from Excellent to Critical.

$$Overall\ Pipeline\ Index = \sum_{r=1}^{5} SCr * r \quad (2)$$

The resulting calculated grade shall range between 1 and 5 (Excellent to Critical). The grade description is interpreted in Table IV. The table provides information about each condition grade with its corresponding overall grade range and description for the decision-makers reference and guidance.

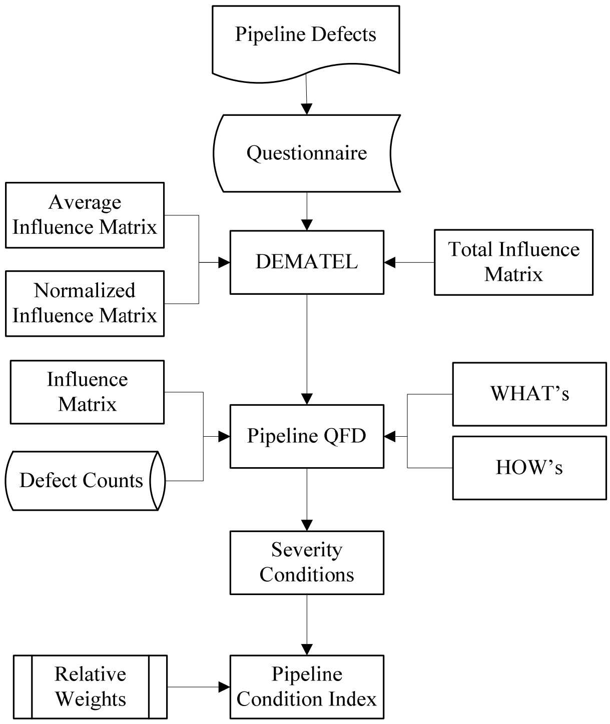

Fig. 4 Proposed methodology

TABLE IV
PROPOSED PIPELINE CONDITION GRADES, CONDITIONS AND DESCRIPTIONS

Overall Grade	Condition	Description
1.00 to <1.50	Excellent	No defects with strong soil support
1.50 to < 2.00	Good	Minor defects are observed with small to medium severities; soil support erosion started with minimal severity.
2.00 to < 3.00	Fair	Moderate defects with medium severity; soil erosion is in progress
3.00 to <4.00	Poor	Major defects with medium to high severity; void erosion is severe.
4.00 to 5.00	Critical	Sever defects are observed. Pipeline collapses or collapse is imminent. Pipeline has lost major of its surrounding soil

V. CONCLUSIONS

This study proposes an enhanced sewer pipeline condition assessment model by adding the void erosion defect and by studying the cause and effect relationship between the defects themselves. The research is still under preparation as the responses are still under analysis. After analyzing the results, the study is expected to demonstrate the relative influence of each defect compared to the others based on causality relationship and to deduce the most influencing and influenced defects in the system. The model will be implemented and validated on actual case studies to test their applicability and reliability. Once completed, the model shall help decision-makers to better assess the condition of the sewer pipelines for maintenance/rehabilitation budget allocation.

REFERENCES

[1] K. Kaddoura, *Automated Sewer Inspection Analysis and Condition*

Assessment. Montreal, QC, 2015.
[2] R. Wirahadikusumah, D. Abraham, T. Iseley, and R. K. Prasanth, "Assessment technologies for sewer system rehabilitation," *Automation in Construction,* vol. 7, 1998, pp. 259 -270.
[3] R. Kirkham, P. D. Kearney, K. J. Rogers, and J. Mashford, "PIRAT—a system for quantitative sewer pipe assessment," *The International Journal of Robotics Research,* vol. 19, 2000, pp. 1033 – 1053.
[4] Y. Kleiner, "Scheduling inspection and renewal of large infrastructure assets," *Journal of Infrastructure Systems,* vol. 7, 2001, pp. 136 – 143.
[5] Canadian Infrastructure, *Informing the Future.* Canada, 2016.
[6] S. Daher, *Defect-based Condition Assessment Model and Protocol of Sewer Pipelines.* Montreal, QC, 2015.
[7] T. Angkasuwansiri, and S. K. Sinha, "Development of a robust wastewater pipe performance index," *Journal pf Performance of Constructed Facilities,* 2014.
[8] K. Kaddoura, T. Zayed, and A. Hawari, "Multi-Attribute Utility Theory Deployment in Sewer Defects Assessment," *Journal of Computing in Civil Engineering*, accepted for publication.
[9] G. Kulandaivel, *Sewer Pipeline Condition Prediction Using Neural Network Models.* Michigan, USA, 2004.
[10] M. Najafi, and G. Kulandaivel, "Pipeline condition prediction using neural network models," *Pipelines 2005: Optimizing Pipeline Design, Operations, and Maintenance in Today's Economy,* 2005, pp. 767-781.
[11] J. Mashford, D. Marlow, D. Tran, and R. May, "Prediction of sewer condition grade using support vector machines," *Journal of Computing in Civil Engineering*, vol. 25, 2010, pp. 283-290.
[12] J. Ruwanpura, S. Ariratnam, A. El-Assaly, "Prediction models for sewer infrastructure utilizing rule-based simulation," *Civil Engineering and Environmental Systems*, vol. 21, 2004, pp. 169-185.
[13] F. Chugjtai, and T. Zayed, "Infrastructure condition predication model for sustainable sewer pipelines," *Jounral of Performance of Constructed Facilities*, vol. 22, 2008, pp. 333-341.
[14] I. Bakry, H. Alzraiee, M. Masry, K. Kaddoura, and T. Zayed, "Condition Prediction for Cured-in-place Pipe Rehabilitation of Sewer Mains," *Journal of Performance of Constructed Facilities*, vol. 30, 2016.
[15] I. Bakry, H. Alzraiee, M. Masry, K. Kaddoura, and T. Zayed, "Condition Prediction for Chemical Grouting Rehabiliation of Sewer Networks," *Journal of Performance of Constructed Facilities*, vol. 30.
[16] American Society of Civil Engineers, *1988 Infrastructure Report Card*. United States, 1988.
[17] American Society of Civil Engineers, *1998 Infrastructure Report Card*. United States, 1998.
[18] American Society of Civil Engineers, *2001 Infrastructure Report Card*. United States, 2001.
[19] American Society of Civil Engineers, *2003 Infrastructure Report Card*. United States, 2003.
[20] American Society of Civil Engineers, *2004 Infrastructure Report Card*. United States, 2004.
[21] American Society of Civil Engineers, *2005 Infrastructure Report Card*. United States, 2005.
[22] American Society of Civil Engineers, *2009 Infrastructure Report Card*. United States, 2009.
[23] American Society of Civil Engineers, *2013 Infrastructure Report Card*. United States, 2013.
[24] American Society of Civil Engineers, *2017 Infrastructure Report Card*. United States, 2017.
[25] L. K. Chan, and M. L. Wi, "Quality function deployment: a literature review," *European Journal of Operational Research,* vol. 143, 2002, pp. 463 – 497.
[26] A. I. A. Costa, M. Dekker, and W. M. F. Jongen, "Quality function deployment in the food industry: a review," *Trends in Food Science & Technology,* vol. 11, 2000, pp. 306 – 314.
[27] I. Dikmen, M. T. Birgonul, and S. Kiziltas, "Strategic use of quality function deployment (QFD) in the construction industry," *Building and Environment*, vol. 40, 2005, pp. 245 – 255.
[28] C. P. Govers, "What and how about quality function deployment (QFD)," *International Journal of Production Economics,* vol. 46, 1996, pp. 575 – 585.
[29] G. H. Tzeng, C. H. Chiang, and C. W. Li, "Evaluating intertwined effects in e-learning programs: A novel hybrid MCDM model based on factor analysis and DEMATEL," *Expert Systems with Applications*, vol. 32, 2007, pp. 1028 - 1044.
[30] J. P. Davies, B. A. Clarke, J. T. Whiter, and R. J. Cunningham, "Factors influencing the structural deterioration and collapse of rigid sewer pipes," *Urban Water*, vol. 3, 2001, pp. 73 – 89.