Frame Work of Condition Assessment for Sewer Pipelines

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Abstract

The civil infrastructure including highways, bridges, and water/sewer systems, is crucial for economic growth and prosperity. Among the various infrastructure systems, sewer pipelines networks represent a great challenge due to their diverse components that have different repair requirements. This paper introduces a comprehensive asset management framework to support the efficient planning of maintenance and repair programs for sewer pipelines. The advantages of the proposed framework stem from the following: 1) a simple approach to support the assessment of the current condition of defects associated with gravity sewer pipelines; 2) a Markov chain approach for prediction of future conditions along the planning horizon; and 3) a GA-based optimization algorithm for determining the least-cost strategy to repair pipeline deficiencies in each year of the planning horizon. A case study of Shoha sewer network in Dakhlia, Egypt is presented to demonstrate the capabilities of the developed frame work. The results showed the effectiveness of the proposed framework in making appropriate decisions that ensure the sustainable operation of sewer pipelines networks.

I. Introduction

Civil infrastructure is the foundation for economic growth, a large percentage of its assets are rapidly deteriorated due to age, harsh environment, and insufficient capacity. Governments, municipalities and organizations, therefore, have come under increasing pressure to develop new strategies to manage public assets in a way that ensures their long-term sustainability. With the huge shortage in expenditures, maintaining the operation of infrastructure facilities becomes a challenge that requires various efforts related to facility condition assessment, resource planning and rehabilitation techniques. This requires the search for innovative and new developments that can achieve substantial benefits in terms of cost savings and least interruption to the public.

In Egypt, for example,Indicators show that 85% of rural residential buildings in rural governorates had some type of sanitary facility in 2002. Nearly 10% of buildings were sewered, the other 75% had some type of on-site storage (Septic tanks or house vaults) (MWRI - 2005). The Government of Egypt, increasingly aware of the rural sanitation problem, is committed to implement the National Program for Rural Sanitation in Egypt through the Ministry of Housing, Utilities, and Urban Development. The scale of the program is national, and program interventions are expected to touch nearly every village and household in the Nile Valley and Delta. A well-conceived strategy based on an informed analysis of problems, participants, objectives, and alternatives is needed. This strategy is required to ensure that the limited program resources, plus additional resources leveraged by the program will achieve the program's objective; as the hazards of this problem do not affect only environment and public health, but also the objectives of water resources management strategy in Egypt (World Bank 2005). In the last decade, infrastructure asset management has emerged as a formal approach that combines engineering and economic principles to cost effectively maintain and upgrade infrastructure assets; for example, Wirahadikusumah et al. (2001) introduced a Markov chain based deterioration model for different group of sewer pipes. Data from large diameter combined sewers in the City of Indianapolis are classified into 16 groups based on types of material, ground water table (GWT), backfill soil type, and depth of cover. Transition probabilities are estimated for each group of pipes using exponential models. Due to limited availability of data, transition probabilities are derived only from one group of data.Chughtai and Zayed (2008) developed a condition prediction model using multiple regressions technique using data collected from two municipalities in Canada. A separate deterioration model is developed for each type of material, i.e. concrete, asbestos, cement, and PVC pipes. The models show 80 to 86% accuracy when they are applied to a validation dataset. This accuracy level is considered very high. Because of the complexity of asset management operations, the targets of maintenance programs need to be tuned to reach near optimal solution for cost savings and other important objectives like resources, time, and quality. As the space of the problem depends on fairly large amount of data and multiple variables, GAs can provide excellent support for handling such type of problems. Performance indicators present the essential data for commencement of optimization process (Wang et al. 2003). Final step for decision maker is to get near optimal solutions that assist the selection of the relevant budget with restricted fund. The current paper presents a comprehensive asset management framework for sewer pipelines networks. The proposed framework is composed of three main modules: condition assessment to access the current conditions of pipes; Markov chain module to predict the future conditions of pipes and an optimization module to optimally identify the repair strategy. A real-life case study project is used to demonstrate the applicability of the developed system.

II. Condition grading of Sewer Networks

The overall approach to condition assessment of sewer pipes can be broadly classified into structural condition and serviceability condition. Examples of common structural defects include fracture, crack, deformation, surface damage and sag. The serviceability deterioration is also a continuing process that reduces the discharge capacity of the pipe and can be observed through a reduction of cross-sectional area and an increase in pipe roughness due to roots,debris,encrustation and infiltration(WRC 1994).

In assessing the condition of a sewer pipeline, this task consists of three steps (Tran 2007) .As following:

(1) Selection of monitoring frequency,
(2) Selection of inspection techniques and
(3) Grading of pipe conditions.

1- Monitoring frequency

Bridges and pavements are subjected to a regular (or repeated) inspection program to identify structural defects during their lifetime. In particular, every bridge is legally required to be inspected once every two years (Madanat et al. 1995). Unfortunately, sewers pipes were not subjected to such regular inspection programs. Instead, their inspection programs were of snapshot type, that is, a sample of pipes was inspected for only once (Kathula 2001).

2- Inspection Techniques

This basic step often associates with reviewing as-built drawings and existing information in order to form the backbone of any management database. This task continues throughout service lifetime of the pipe systems whenever new information such as pipe replacement or repair occurs.

There are several inspection techniques available for each level of assessment, there are no guidelines for selecting these techniques for a particular application. In order to reduce time and effort in selecting the appropriate inspection technique, a number of researchers have provided comprehensive reviews of inspection techniques that were applied in many infrastructure facilities(Tran 2007).

3- Grading of pipe condition

The Water Research Center (WRC) in UK devised the world first condition grading scheme that provided protocols and guidelines for assessing current condition of individual pipes using the Closed Circuit Television(CCTV) inspection technique (WRC 1983). Based on the original scheme of WRC (1983), several condition grading schemes were later developed in Canada (McDonald and Zhao 2001) and Australia (WSAA 2002). Although the structural and serviceability deterioration of pipes are a continuous, ordinal grading systems were used in these schemes for mapping the pipe deterioration into pipe conditions at the time of inspection. For example: The Sewer Inspection Reporting Code (SIRC) by the Water Service Association of Australia (WSAA 2002) was developed for assessing conditions of rigid sewers (concrete and vitrified clay pipes) using CCTV inspection data as shown in Table 1.

Table 1: Description of condition states used in WSAA (2006)

Condition Grading	Structural condition	Serviceability Condition
1	Insignificant deterioration of the sewer has occurred. Appears to be in good condition	No or insignificant loss of hydraulic performance has occurred. Appears to be in good condition
2	Minor deterioration of the sewer has occurred.	Minor defects are present causing minor loss of hydraulic performance
3	Moderate deterioration has occurred but defects do not affect short term structural integrity	Developed defects are present causing moderate loss of hydraulic performance
4	Serious deterioration of the sewer has occurred and affected structural integrity	Significant defects are present causing serious loss of hydraulic performance
5	Failure of the sewer has occurred or is imminent	Failure of the sewer has occurred or is imminent

the grading process based on the SIRC for a pipe segment from CCTV data. A pipe segment is defined between two manholes or pits. As shown in Figure 1, the CCTV robot was sent to the pipe of interest. During its movement along the pipe, the CCTV-recoded images were sent to a monitor where the operator can recognize any structural or serviceability defects. He or she then coded the defects with the aid of computer; each coded defect was automatically or manually assigned a score according to the guidelines of weights. For example a structural defect like crack has a score of 5. All defect scores were aggregated for two condition measures, namely, peak score and mean score. The peak and mean score were then compared against pre-defined thresholds for grading the pipe into either condition one, two or three. In general, structural defects that receive high scores are surface damage, breaking and deformation, while debris, roots and obstruction get high scores for serviceability defects. The peak score indicates the largest score from one defect or multiple defects in one location (often within a meter length) in the pipe segment. The mean score is the sum of all defect scores divided by the segment length (Tran 2007).

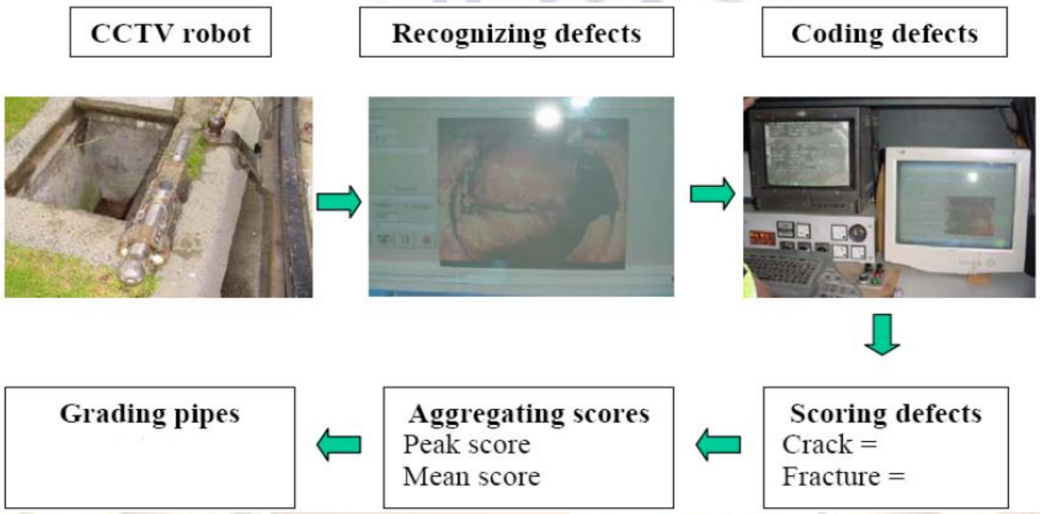


Fig. 1: Grading process for a pipe from CCTV data

Chugai and zayed(2008) expressed the physical grade of the sewer pipeline by combining the effects of structural and serviceability rates as shown in Equation 1 , Table 2 and Table 3.

Pipe Condition Grade (Physical Condition) =

$$\sqrt{0.541+0.273\,(R_{str.})^2+0.37\,(R_{ser.})^2} \quad (1)$$

Table 2: Structural condition rating (ASCE 1994)

Score range	Structural condition rating, R_{str}
0	0
1-4	1
5-9	2
10-14	3
15-19	4
20	5

Table 3: Serviceability condition rating (ASCE 1994)

Score range	Serviceability condition rating, R_{ser}
0	0
1-2	1
3-4	2
5-6	3
7-8	4
9-10	5

III. Optimization Module

In this model, a more global outlook on decision process is proposed. The model is modified to deal with dynamic policies of cost and condition. These modifications render the model to develop network – level condition assessment. In particular, theGenetic Algorithm is used to determine the optimum time and cost.

IV. Genetic Algorithm Formulation

The proposed representing of the Life Cycle Cost Analysis (LCCA) variables in the optimization module shown in Figure 2. Each pipeline is arranged in a separate row, and three columns are set to hold the values for the problem variables in the three-year planning horizon. These values represent indices for one of the four repair options. In this representation, the variables are the repair decisions for all the pipelines throughout the three-year planning horizon. A number one assigned for year one of pipeline one means that this line is selected for repair in the first year (network-level decision) and that the selected repair strategy is type 1 (project-level decision). It is noted that in this basic problem formulation, the number of variables involved is N × T, and each variable can take an integer value from 0 to 3, corresponding to one of the repair options. The solution structure for this representation is shown in Figure 2.

The objective function is constructed by summing the present values of the annual cost of repairs for all pipelines (Equation 2). The objective function is to minimize the total life cycle cost (LCC) while maintaining an acceptable pipeline condition:

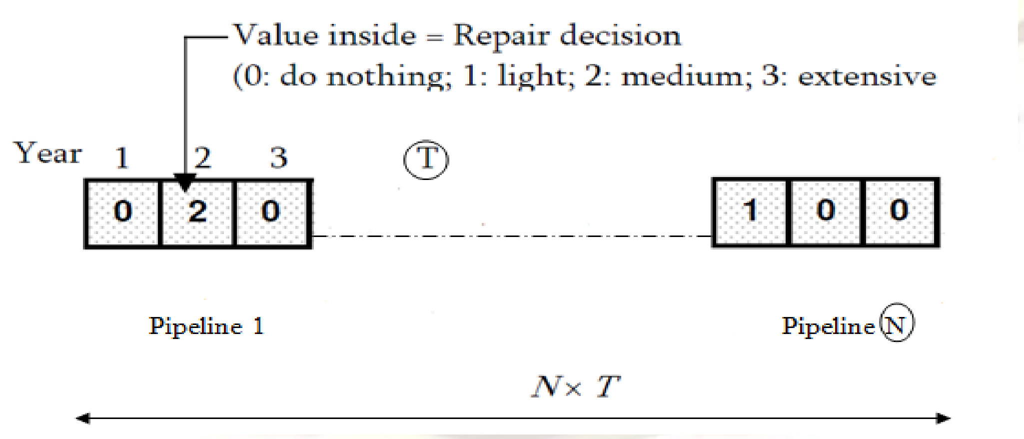


Fig. 2: Solution Representation

$$\text{Min LCC} = \frac{1}{(1+r)^t} \sum_{t=1}^{T} \sum_{i=1}^{N} (C_{ti}) \qquad (2)$$

Where C_{ti} = the repair cost of repair i at time t, r = the discount rate, T = the number of years, and N = the number of pipelines. In addition to constructing the objective function, the proposed optimization module accounts for the following constraints:

- Acceptable level of Improvement is good.
- Planning Horizon 3years.
- Once Repair option is applied through planning horizon for each pipeline.

Given a best repair scenario for a given pipeline, after asking consultants engineering the after-repair condition index of this pipeline can be followed by two assumptions as shown in Table 4:

Table 4: Purpose of repair programs

Proposed Option	Condition Grade After Repair
Replacement	Excellent
Major or Minor	Good

The years after the repair, the pipeline condition will still deteriorate. In this study, it is assumed that after-repair deterioration will follow the same custom deterioration curve obtained from Markov Chain for that instance that we will present in case study.

V. System Development and Case Study

The data for the case study selected for testing the proposed sewer Pipelines Management System (SPMS) were collected from the department of Geographical Information System abbreviated as (DOGIS). The DOGIS has adopted the Shoha Water and Sewer System (SWSS). However, the SWSS is not fully utilized and is used only for data storage, not for tracking the performance of the network, or for inspection reports. The DOGIS owns and operates 29000 km of sewer lines, data for 10 pipeline were provided by the DOGIS as a case study for the SPMS developed in this study. Some of the data were also collected through interviews with engineers from the company. The data included general information about the sewer network, such as the Pipeline ID, the pipeline Type, the manhole ID, the Manhole Levels for inlet and outlet pipes, the pipe material, the Pipeline length (m), the Pipe diameter (mm).

Evaluating of the condition state of infrastructure specifically in sewer pipelines is one of the most integral pieces of information to the asset manager. Assessing the condition state has tremendous implications on operations, maintenance and renewal, a reliable measure for condition state can be a daunting task compared to surface infrastructure. During interviews with engineers at the department of technical support (DOTS) the direct inspection tool is not available to the company but condition assessment decisions for network elements depends on:

- The complaints from the hot line service: for the case study of sewer Shoha network has no sever complaint there only temporary blockage in winter due to misuse.
- The aging of material used in Vitrified Clay pipes (VC) according to manufacturing specifications.
- Hydraulic calculation checks for pipelines transition efficiency and capacity according to present population in 2013 (60000 capita).

Finally the current condition estimated now Good Grade (2-3).

The cost data were collected through interviews with the Department of construction (DOC) engineers, and from previous DOC contracts and using of CAD drawings and contract documents for sample of pipes; it was possible to obtain unit prices for repair activities for different pipelines. Table 5 shows a summary of the estimated repair/replacement costs.

Table 5: Cost Data for the Case Study

Element	Repair option	Unit	Unit Price LE
Vitrified clay (VC) pipeline Diameter (175 mm) Depth (2-2.5 m)	▪ Minor (Spot Grouting) ▪ Major (Partial Lining) ▪ Replacement	m m m	140 (20% of replacement) 420 (60% of replacement) 700

The condition assessment module is implemented on a spreadsheet program; Figure 3 shows the main screen of thecondition assessment module. An example of a pipeline used for determination of current grad and condition index. The example consists of Structural defects, in addition to Serviceability and a level of each defect is required.

The user needs to follow two steps to use the template and, or adapt it, to model a given pipe line.

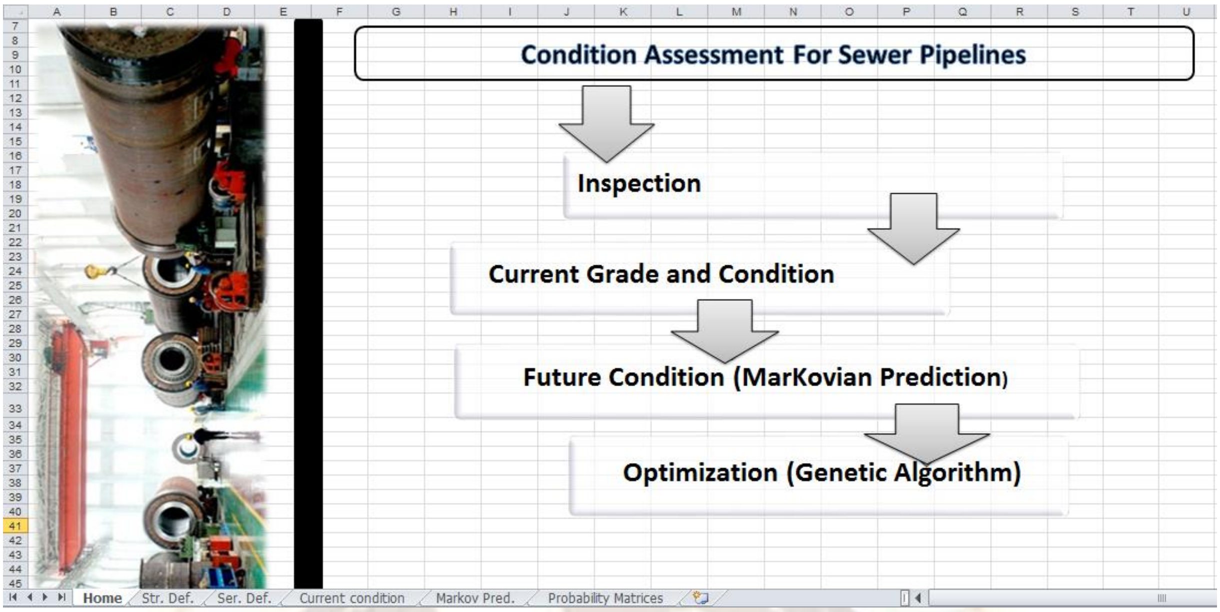


Fig. 3: Main screen of condition assessment of sewer pipelines

- Step 1:

User starts by opening the main screen and clicking to the inspection button (first module), then the structural defects spread sheet will appear as shown in Figure 4.

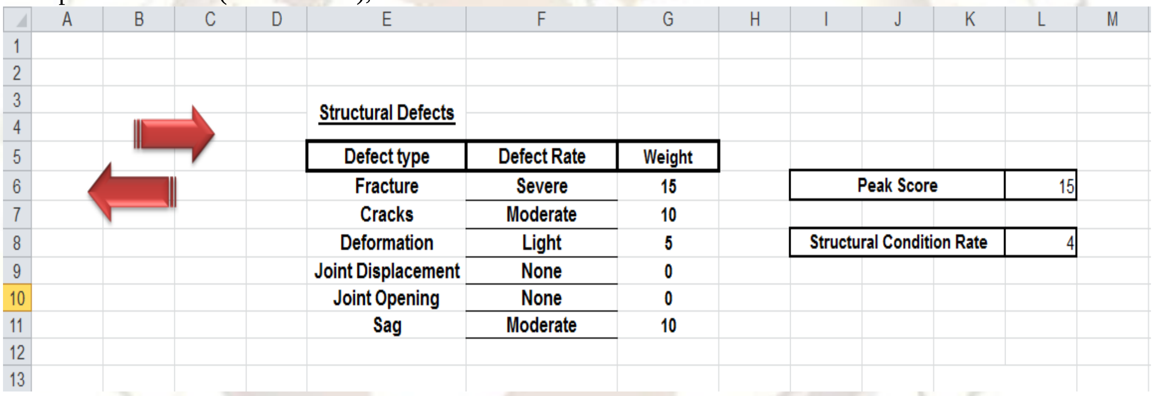


Fig. 4: Spread sheet of structural defects

- Step 2:

Now user will select the real rate (None, Light, Moderate or Severe) of each structural defect (Fractures, cracks, deformation, joint displacement, joint opening and sag) as shown in Figure 5.

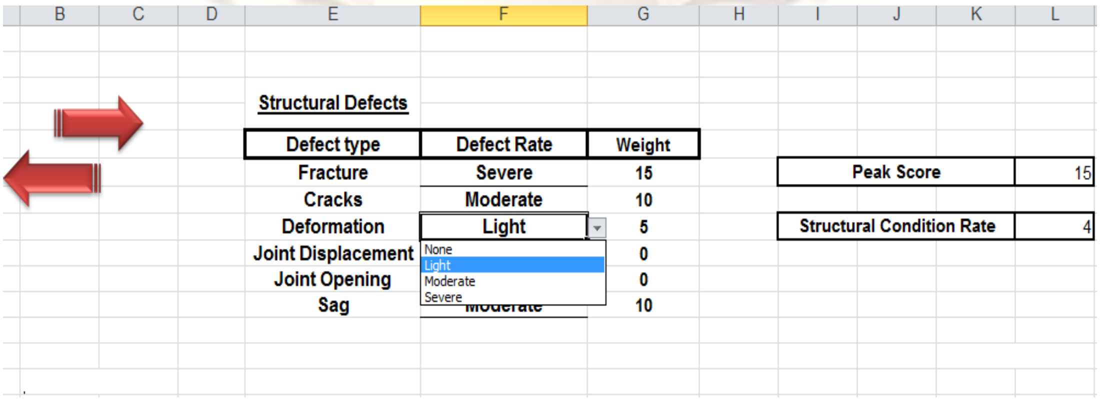


Fig. 5: Selection of structural defects rates

After a complete selection of each defect rate the weights, peak score and structural condition rate determined automatically. Then user can move forward to serviceability defects spread sheet by clicking on forward arrow, the spread sheet will appear as shown in Figure 6.

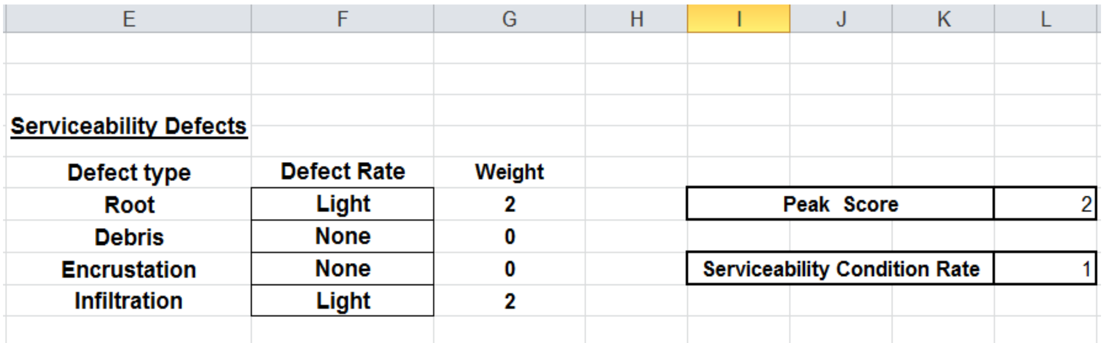


Fig. 6: Spread sheet of structural defects

As previous, users will select the real rate (None, Light, Moderate or Severe) of each serviceability defect (Roots, Debris, Encrustation and infiltration). Then weights, peak score and serviceability condition rate determined automatically as shown in Figure 7.Finally user can get the current grade and condition index by clicking on forward button as shown in Figure 8.

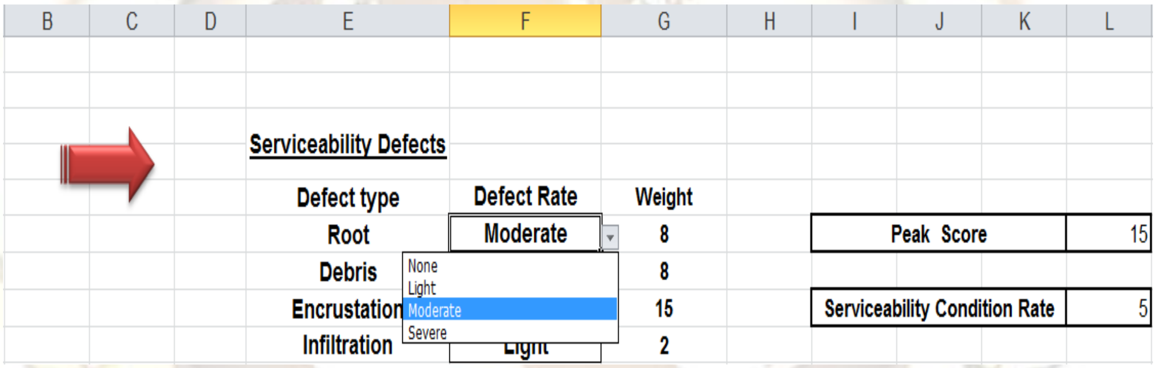


Fig. 7: Selection of serviceability defects rates

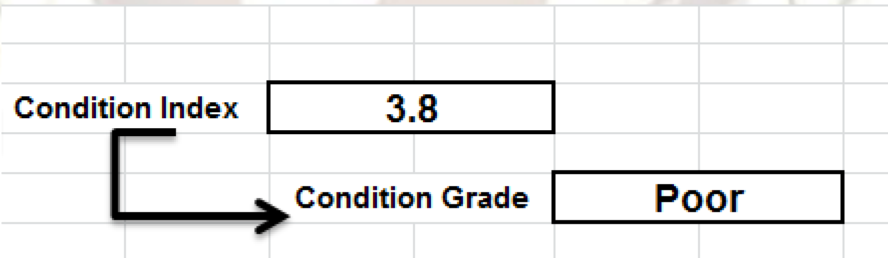


Fig. 8: Condition index and pipe grade

The next approach predicts the deterioration of a component by accumulating its probability of transition from one condition state to another over discrete time intervals using Microsoft Excel.

A summary of the steps to predict the condition at any time (t) is as follows:

1- Open the module of (Markovian Prediction) in a main screen of condition assessment of pipelines as shown in Figure3

2- Define the number of condition states (n) that can describe the deterioration and arrange the possible states [PS] in a column vector as shown in Figure 9. A five-state vector (from 1 to 5) is used, as follows: Excellent condition (1), Very Good Condition (2), Good Condition (3), Poor Condition (4) and Fail Condition (5)

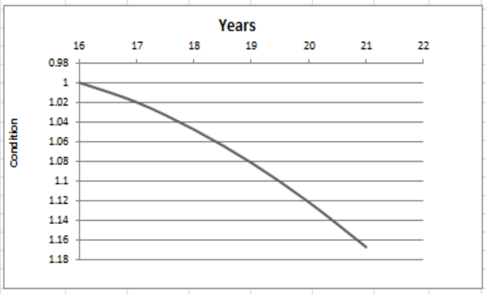
State	1	2	3	4	5
IPo	1	0	0	0	0

Age
16

T.P.M	State	1	2	3	4	5		Ps
	1	0.98	0.02	0	0	0	1	1
	2	0	0.59	0.41	0	0	1	2
	3	0	0	0.79	0.21	0	1	3
	4	0	0	0	0.01	0.99	1	4
	5	0	0	0	0	1	1	5

Time	Possible State					Predicted State
	1	2	3	4	5	
16	1	0	0	0	0	1
17	0.98	0.02	0	0	0	1.02
18	0.9604	0.0314	0.0082	0	0	1.0478
19	0.941192	0.037734	0.019352	0.001722	0	1.081604
20	0.922368	0.041087	0.030759	0.004081	0.001705	1.12166748
21	0.903921	0.042689	0.041145	0.0065	0.005745	1.167460195

P0		1	2	3	4	5
	1	1	0	0	0	0
	2	0	1	0	0	0
	3	0	0	1	0	0
	4	0	0	0	1	0
	5	0	0	0	0	1



P1		1	2	3	4	5
	1	0.98	0.02	0	0	0
	2	0	0.59	0.41	0	0
	3	0	0	0.79	0.21	0
	4	0	0	0	0.01	0.99
	5	0	0	0	0	1

Condition With Time Curve

Home | Str. Def. | Ser. Def. | Current condition | Markov Pred. | Probability Matrices

Fig. 9: Spread sheet of Markovian Prediction

3- Define the initial probability row vector [IPo], as shown in Figure 10 The initial probability row vector (at time 0) shows a condition of 100% being in state 1 and 0% in the rest of states from 2 to 5.

State	1	2	3	4	5
IPo	1	0	0	0	0

	State	1	2	3	4	5	Ps
	1	0.98	0.02	0	0	0	1
	2	0	0.59	0.41	0	0	2
P	3	0	0	0.79	0.21	0	3
	4	0	0	0	0.01	0.99	4
	5	0	0	0	0	1	5

Fig. 10: Transition probability matrix and probability row vector

4- Calculate the future probability row vector at any time [FPt]. The condition after (t) years from a known condition (e.g., the IPo) can be calculated by multiplying the condition vector at the known condition by the [TPM] raised to the power (t).

5- Calculate a single value for the condition (i.e., the future state value FSt). The final step is to come up with one value to describe the condition. This is obtained by multiplying the future probability row vector [FPt] by the possible states column vector [PS].

Since the above process predicts the condition state at any time (t), it can be repeated with various (t) values (1 to 5, for example) to draw a deterioration behavior for 5 years. As explained, all calculations depend on matrix multiplication, which suits spreadsheet platforms. Hence, a spreadsheet model for Markov has been developed.

The DOGIS has no deterioration model for predicting future element conditions. The process of deciding whether the pipeline requires a repair is based on users' complaints. There is also no deterioration model for estimating the impact of a specific repair option on the element condition. Thus, the deterioration and model used in the case study were adopted as shown in Figure 11.

T.P.M

State	1	2	3	4	5
1	0.81	0.18	0.01	0	0
2	0	0.6	0.36	0.04	0
3	0	0	0.68	0.14	0.18
4	0	0	0	1	0
5	0	0	0	0.98	0.02

Time	Possible State					Predicted State
	1	2	3	4	5	
16	0	1	0	0	0	2
17	0	0.6	0.36	0.04	0	2.44
18	0	0.36	0.4608	0.1144	0.0648	2.884
19	0	0.216	0.442944	0.256816	0.08424	3.209296

	0.81	0.18	0.01	0	0
	0	0.6	0.36	0.04	0
P1	0	0	0.68	0.14	0.18
	0	0	0	1	0
	0	0	0	0.98	0.02

	0.6561	0.2538	0.0797	0.0086	0.0018
	0	0.36	0.4608	0.1144	0.0648
P2	0	0	0.4624	0.4116	0.126
	0	0	0	1	0
	0	0	0	0.9996	0.0004

	0.531441	0.270378	0.152125	0.031674	0.014382
	0	0.216	0.442944	0.256816	0.08424
P3	0	0	0.314432	0.599816	0.085752
	0	0	0	1	0
	0	0	0	0.999992	0.000008

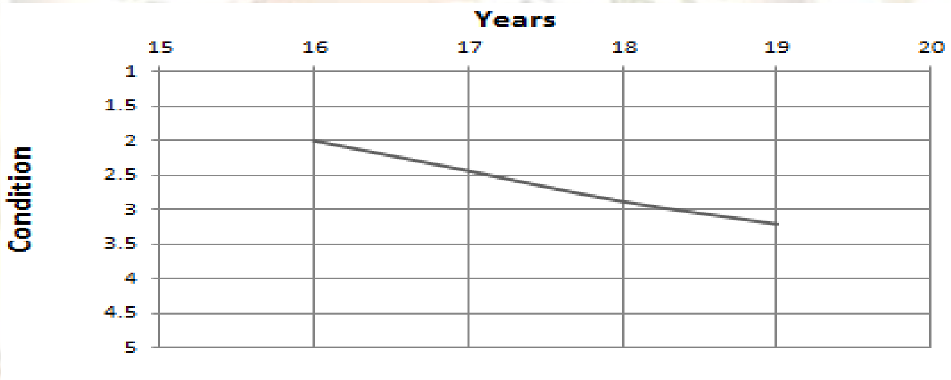


Fig. 11: Markov Chain Prediction Condition within 3 Years

Table 6: Population, Crossover, Mutaion and generations

Mutation =0.06				Mutation= 0.08			
No.	Crossover	Pop.	Gen./ Cycle	No.	Crossover	Pop.	Gen./Cycle
1	0.8	100	100	6	0.8	100	100
2	0.8	50	100	7	0.8	50	100
3	0.8	30	100	8	0.8	30	100
4	0.8	20	100	9	0.8	20	100
5	0.8	10	100	10	0.8	10	100
Mutation = 0.09				Mutation = 0.08			
No.	Crossover	Pop.	Gen./ Cycle	No.	Crossover	Pop.	Gen./ Cycle

11	0.8	100	100	16	0.5	100	100
12	0.8	50	100	17	0.6	50	100
13	0.8	30	100	18	0.7	30	100
14	0.8	20	100	19	0.2	20	100
15	0.8	10	100	20	0.1	10	100

In all experimental solution, the system stopped when the value of the objective function (LCC) did not improve after three consecutive cycles. The parameter settings used in the experiments are shown in Table 6.

From previous 20 experiments to approach near optimum solution we note the following:

- With increasing population size improves the results (Better Condition and Lower LCC) to certain limit, Population 20 to 50 give better results.
- Increasing Mutaion after 0.08 didn't improve results.
- The Figure 12 Shows near optimum Cost and Condition Solution After applying proposed repair program.(Mutation = 0.08, Crossover = 0.08, Pop. Size = 50)

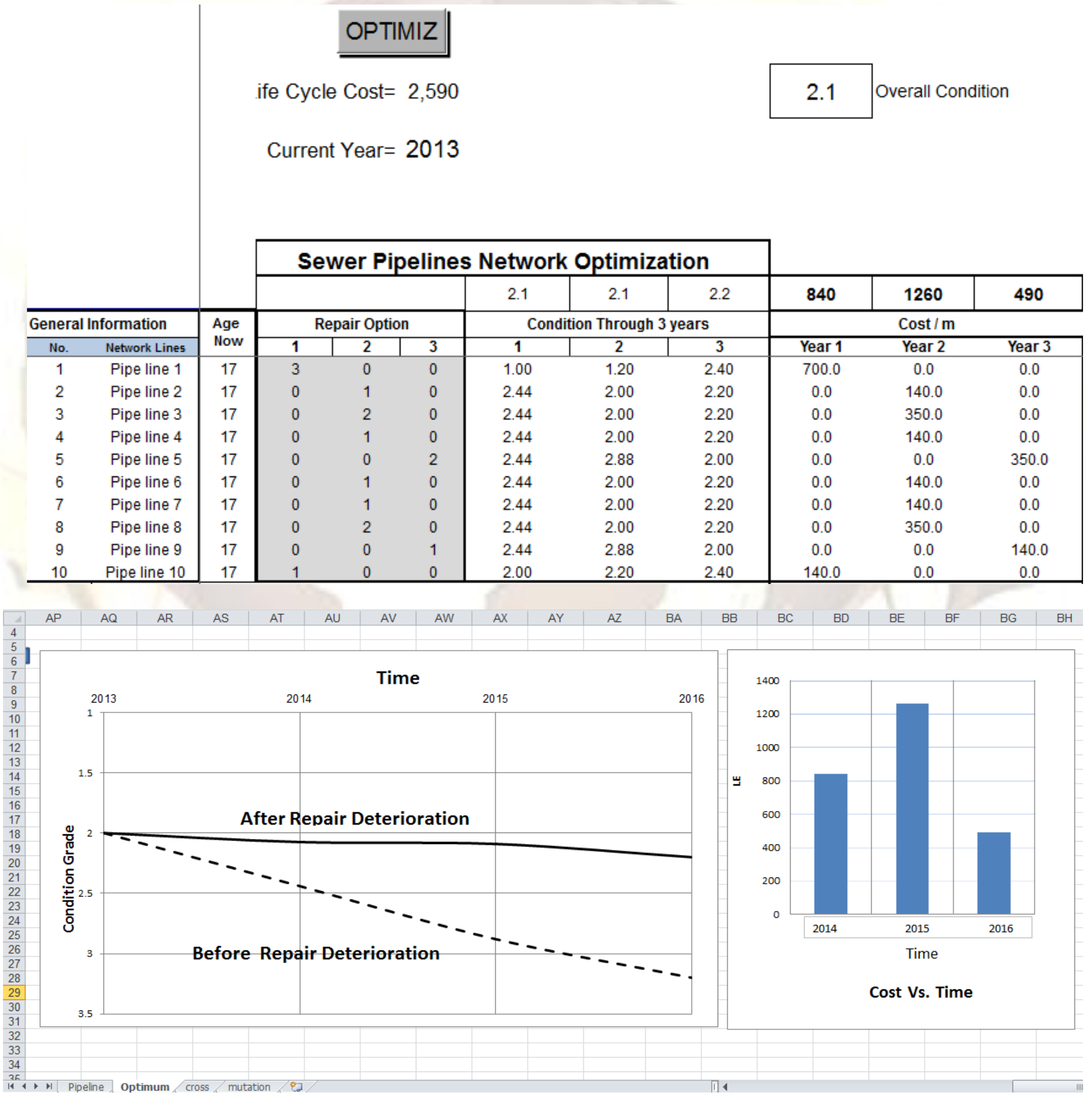


Fig. 12: Near Optimum Solution

VI. Framework Validation

Through interviews and asking to 10 of command, expert and decision taker persons in National-Authority for water and sewer in Dakahliya , water and sewer company in Dakahliya and consultant engineers of sewerage systems in Mansoura to valid the results from presented model, we discussed the following points:Access To Interface, Interface Design, Interface Look, Range of

variables, Reselection ability, Usefulness, Applicability and Overall Performance.
According to Validation Grade we defined the following in each Questionnaire paper as shown in Figure 5.13, the questionnaire results is 1.71 average score and ranked as "very good" as shown in Table 7.

Table 5.4: Result of Model Validation

Criteria \ User	1	2	3	4	5	6	7	8	9	10	Total	Average
Access to interface	1	3	1	2	2	1	2	2	1	2	17	1.7
Interface design	1	2	2	3	2	1	2	1	2	3	19	1.9
Interface look	2	2	3	2	3	0	2	1	1	2	18	1.8
Range of Variables in each input	3	1	3	3	3	2	2	2	2	2	23	2.3
Access to outputs	2	4	3	0	3	1	2	1	1	3	20	2
Re- selection ability	2	1	3	2	2	1	2	2	1	2	18	1.8
Usefulness	1	2	1	2	2	2	2	3	2	2	19	1.9
Applicability	1	2	1	2	2	2	2	3	2	2	19	1.9
Overall Performance	2	2	2	1	2	2	2	2	1	2	18	1.8
Overall Average												1.71

Excellent	<1
Very good	1-2
Good	2-3
Poor	3-4
Fail	4-5

Very Good

VII. Summary and Conclusion

Condition assessment facilitates the ongoing estimation and tracking of sewer asset condition. The lack of reliable condition data is a tremendous impediment to any asset management program. Condition assessment is costly and uncertain for sewer networks compared with other surface infrastructures. Asset managers need to convince political decision makers that investment in reliable condition data is valuable to their asset management programs. This paper has presented aframework methodology for rationalizing condition assessment policies across sewer networks. An illustrated example of theShoha village sewer network showed how the framework can be deployed. At the asset level, results allow the asset manager to select the most suitable condition assessment strategy and inspection interval for a particular pipe. At network level, results enable the proper allocation of a condition assessment cost through all pipes in planning horizon. The developed framework integrated with the genetic algorithm optimization process. The following impediments may prevent the use of this system:

1- Difficulty in obtaining information of current condition and aging of sewer pipes .
2- Public awareness and funds for sewer network environments.

In spite of these limitations, the developed framework serves as a starting point for asset managers to set their condition assessment policies on the basis of a methodical process rather than a gut feeling. Further work is currently underway to Test the condition assessment module individually in an actual assessment survey to determine its performance. Also, expanding the visual guidance system with pictures of various deteriorating components and Using GIS and visualization techniques to present the system outputs such as condition indices, level of funding, backlog, and actual versus planned performances.

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