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Assessment of bridges' expansion joints in Egypt

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ASSESSMENT OF BRIDGES' EXPANSION JOINTS IN EGYPT

A thesis submitted to the Department of Construction Engineering
in partial fulfillment of the requirements for the
Master of Science Degree in Construction Management

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ABSTRACT

Bridges play a vital role in resolving transportation problems in Egypt. The objective of this research is to predict the conditions of bridges expansion joints, with the aim of proposing appropriate maintenance and repair strategies in order to extend their lifespans. A thorough literature review of existing bridges expansion joints maintenance and repair strategies are conducted. Furthermore, visual inspections and surveying of existing bridges expansion joints in Egypt are conducted, with the findings of such observations documented and recorded.

Moreover, an expansion joint management system (EJMS) is developed with the aim of recommending the optimum maintenance strategy for bridges that optimizes annual condition index (ACI) and cost. This model uses a combination of Fuzzy Logic (FL) and Genetic Algorithm (GA) in order to provide optimal recommendations. In addition, a transition matrix for predicting deterioration of expansion joints EJ using Markov Chain (MC) is developed.

In order to test the model, several case studies of existing bridges in Egypt are used and the results are assessed against those documented through visual inspection. The comparison indicated that the developed EJMS is efficient in predicting the bridge EJs condition, where there is a deviation of 5% between the predicted condition from EJMS and the actual conditions observed through visual inspections. In addition, EJMS can play an important role in supporting decision makers in selecting the optimum maintenance and repair strategy that would maximizes the overall condition of expansion joints while meeting a certain budget constraint.

Keywords: Bridges - Expansion joints - Deterioration Model - Fuzzy Logic – Optimization

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To my Father, Mother, Wife, Brothers and Sisters

DEDICATION

This thesis is dedicated to my source of inspiration, my beloved parents and to my beautiful wife (***Dr. Noura Bahaa***) for their encouragement, guidance and happiness, with whom the goals and aspirations are shared. May ***ALLAH*** bless and protect them, in addition to giving me the strength to ever repay them for their kindness.

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LIST OF ABBREVIATIONS

AADT......................... *Annual Average Daily Traffic*

ACI .... *Annual Condition Index*

ADT .... *Average Daily Traffic*

ANN........................... *Artificial Neural Network*

APJ.......................... *Asphalt Plug Joint*

BMS........................... *Bridge Management System*

CS .... *Compression Seal*

EJ............................... *Expansion Joint*

EJMS......................... *Expansion Joints Management System*

FHWA .... *Federal Highway Administration*

FL .... *Fuzzy Logic*

GA.............................. *Genetic Algorithm*

IA .... *Integral Abutment*

LCC .... *Life Cycle Cost*

LCCA......................... *Life Cycle Cost Analysis*

MADT........................ *Monthly Average Daily Traffic*

MBEJ .... *Modular Bridge Expansion Joints*

MC............................. *Markov Chain*

MDP .... *Markov Decision Process*

PMS........................... *Project Management System*

RCI .... *Roof Condition Index*

S.S.............................. *Strip Seal*

TLCC…………………..*Total Life Cycle Cost*

CHAPTER 1
INTRODUCTION

CHAPTER 1
INTRODUCTION

Bridges offer solutions to a number of transportation problems. They are used to solve intersection problems, overcome bodies of water, as well as connecting islands and landmasses. Moreover, they are used to carry trains, vehicles or pedestrian traffic, as well as carrying pipelines, waterways with barges or Aircraft runways. Furthermore, bridges can offer solutions to areas that have been poorly planned, or where a lack of planning is evident.

Bridges form a vital element of any cities' lifeline system. Accordingly, closing up these Bridges for maintenance could paralyze any city. Thus, it is essential to select an appropriate system for assessment and maintenance of these bridges, in order to maintain durability as well as reducing the need for closure.

Furthermore, bridges are exposed to physical and environmental conditions that can result in their rapid deterioration. Thus, it is essential that their elements are periodically maintained. It is therefore important to assess which of the bridge elements require the most periodical maintenance since these elements will have the greatest influence on the lifetime of the bridge.

According to Marques and de Brito (2009), expansion joints EJs are considered one of the weakest elements in bridges. Their life time is considerably shorter than other bridge elements. This is ascertained by the fact that most joints undergo several interventions during their life time (Marques and de Brito, 2009). This results in added costs that increase the life cycle cost (LCC) of the bridge.

This chapter presents a brief review on the need for bridge repair according to various existing bridge conditions both globally and locally. Moreover, it highlights the advantages of bridge management systems and their main components. In addition, the chapter also presents the research problem definition, research objectives and methodology.

1.1 HISTORICAL DATA ABOUT BRIDGE REPAIR

In order to gain an understanding regarding the current practice of bridge repair, it is essential to first exhibit their historical trends and the need to conduct such repair.

According to the Federal Highway Association (FWHA, 2012) the cost of repair or replacement of deficient or obsolete bridges has been steadily increasing in the US, with the cost rising from 48 billion in 2009 to 70.9 billion in 2012.

Maintenance of old bridges is essential in improving their load carrying capacities and to bring them up to the current standards. As indicated by Fickelson (1990), early maintenance activities minimizes the life cycle cost of bridge elements. Therefore, Maintenance and repair is preferred over rehabilitation and replacement.

According to data collected in 2016, there are currently 444,000 bridges in the US where 65% of all roads are currently not in an acceptable condition. Furthermore, 25% of all bridges require extensive repair, since they currently cannot accommodate the traffic demand. This is vitally important due to the fact that it is estimated that US citizens currently lose 6.9 million hours in traffic per year due to poor road conditions, which translates into 160 million USD of additional fuel expenses annually. Accordingly, the US government has requested the inclusion of $478 billion for transportation maintenance for the next 6 years, of which $51.3 billion will be used in 2016 only for improving the safety and supporting critical infrastructure (USDOT, 2016).

Based on a study conducted by the US Department of Transportation (2016), the number of deficient bridges has increased by 1.5% from 2008 to 2014, with the number of deficient bridges currently standing at 9,000 bridges. Moreover, during this same time frame, the number of bridges exhibiting fair condition has increased by 2% (USDOT, 2016).

Figure 1-1 presents a breakdown of US bridges by age, while Figure 1-2 presents a breakdown of the percentage of deficient bridges in the US by age. The percentage of bridges, classified as structurally deficient, increases as their age increases. Nevertheless, 8.2 % of bridges of 26-50 years of age are structurally deficient, while this percentage is 18.0 % for 51-75 years of age and 29.2 % for 76-100 years of age (FHWA, 2016).

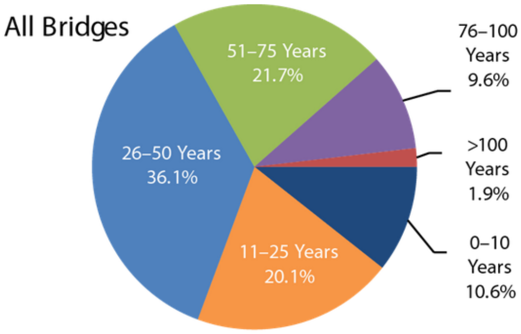


Figure 1-1 Percentages of Bridges by Age, 2012 (FHWA, 2016)

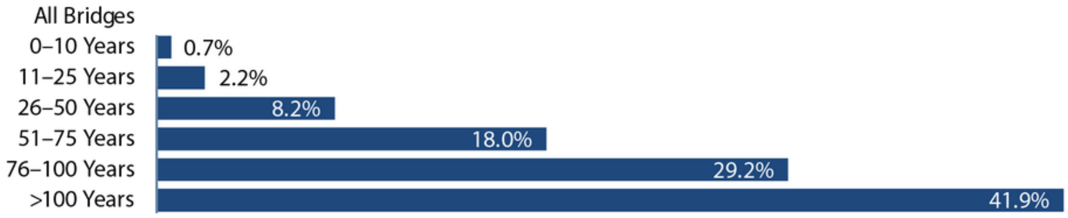


Figure 1-2 Percentages of deficient bridges by Age, 2012 (FHWA, 2016)

The increasing cost of repair has been evident not just in the US but globally. According to SETRA (2015), the Technical Studies Department of French Highways, the cost of maintaining EJs is estimated to be between 7-8% of the global maintenance costs of bridges. Moreover, this percentage has been seen to rise to 25% for the main highways concessionary in Portugal. (SETRA,2015)

According to Gaudreault (2006), bridges compromise the highest investment and capital stock division versus other essential lifelines in Canada (Figure 1-3). Their cost has increased by approximately 43% between year 1963 and year 2003, thus significantly increasing the overall cost of maintenance of Canada's infrastructure and lifelines. This cost is expected to increase further since 60% of Canada's 8000 bridges are currently more than 30 years old, thus approaching their life expectancy and potentially requiring major rehabilitation.

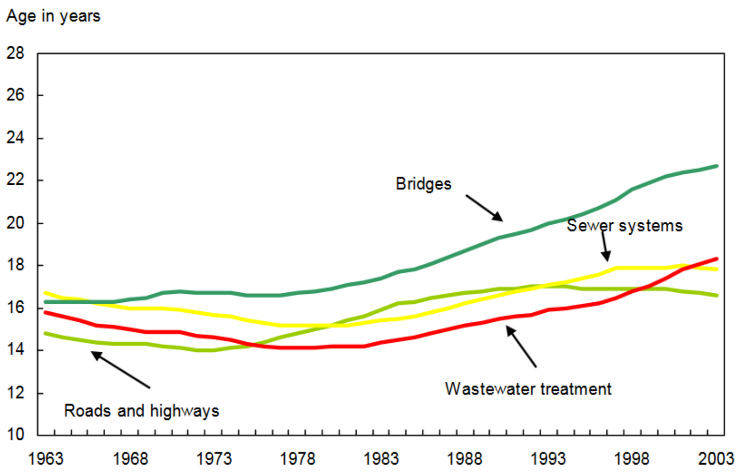


Figure 1-3: Investment and Capital Stock Division in infrastructure in Canada (ICSD's, 2006)

1.2 BRIDGE MANAGEMENT SYSTEM (BMS)

With the ever increasing number of highway bridges and the associated cost of maintaining such structures, governmental authorities have developed tools for managing them. Bridge Management Systems (BMS) are developed to manage network of bridges while considering the available resources. A number of BMS systems are available to assess bridge conditions, predict deterioration rate, measure the traffic effect, estimate the residual lifetime, and establish bridge's maintenance plan. The main focus of such systems is to consider the bridges on both network level and project level, in order to decide on the maintenance plans for these bridges based on available resources and priorities.

In order to establish a BMS that is capable of supporting the decision making process, it should incorporate a number of modules that are to be integrated with one another within an overall framework. These modules would include; bridge stock inventory; bridge condition and age; risks induced by users (i.e. load carrying capacity), in addition to costs of maintenance plans; deterioration forecasting; socio-economic importance of the bridge; optimization according to certain budget constraints and maintenance priorities. Figure 1-4 presents framework of a BMS developed by (Woodward et al., 2001), which shows these modules along with the interfacing between them. The framework considers the two management levels, network and project levels.

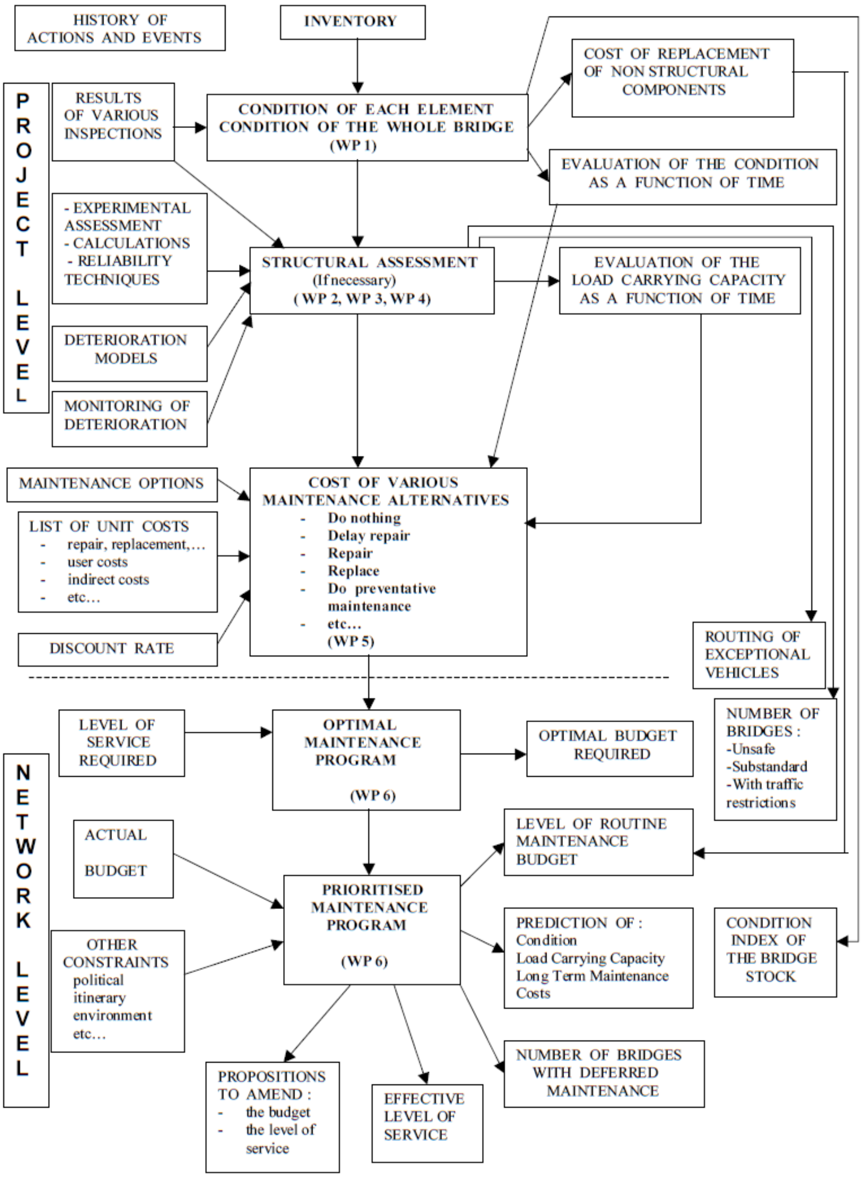


Figure 1-4 Framework of a BMS (Woodward et al., 2001)

1.3 PROBLEM DEFINITION

The Egyptian network of bridges forms a critical network in the nation's infrastructure. Accordingly, it is essential that the lifespan of these structures is extended to reduce potential closures and consequently crippling of Egypt's transportation network. In order to extend the lifespan of these bridges, EJs need to be maintained since they are the weakest element in the bridge's structure. Nonetheless, a lack of information is available regarding current conditions of

EJs in Egypt, as well as the deterioration rates of such elements. Accordingly, thorough evaluation of the current condition of EJs needs to be conducted, in addition to forecasting the deterioration rate of these elements in order to predict their future state.

Furthermore, in order to reduce the lifecycle cost of the bridge, an optimal maintenance plan for EJs needs to be selected. Accordingly, developing an expansion joint management system (EJMS) would be a great benefit to provide decision makers with the optimal maintenance plan that will in turn reduce the life cycle cost of the bridge.

1.4 RESEARCH SCOPE AND OBJECTIVES

The goal of this research is to build a comprehensive expansion joint management system in Egypt (EJMS), which offers a tool to transportation agencies and decision makers in optimizing EJ maintenance plans and repair strategies over a number of years, within a given budget, so that feasible and practical plans can be set forth. Furthermore, in order to serve the needs of road operators, the system needs to consider both element-level and project level. This will lead to a more efficient application of EJMS, with a higher level of service delivered to the end road user at a lower cost.

Detailed research objectives include:

1. Developing an integrated element-level project management system that assess the condition of EJs in Egypt.
2. Determining the transition matrix of EJs in Egypt to be able to predict their deterioration over time.

3. Developing an integrated project-level management system that is capable of obtaining the optimum maintenance plan for a bridge, to meet certain project constraints (budget and overall condition) that maximizes the overall EJ conditions under a certain budget constrains
4. Determining the optimum EJs maintenance and repair strategy over a number of years to achieve a minimum acceptable project condition.

1.5 RESEARCH METHODOLOGY

Based on the previously stated objectives, this research passed through six main stages as shown in Figure 1-5. Theses main stages are: Definition, Clarification, Design, Develop, Verification and Validation.

Figure 1-5 Research Methodology

1. ***Definition Stage:*** This stage presents reviewing the literature on bridge management tools and methods. It also includes a thorough review of EJs and methods used for condition assessment, deterioration prediction, and optimization for bridges maintenance and repair.

2. ***Clarification Stage:*** The clarification stage focuses on the Egyptian bridge inventory, especially on EJs of Egyptian bridges. It also includes conducting visits to several bridges in Egypt to be acquainted with different types of EJs used and the problems encountered.

3. ***Design Stage:*** This stage focuses further on the problem statement, presenting the design methodology for tackling this problem.

4. ***Develop Stage:*** In this stage an integrated model is developed to assess and predict the conditions of the bridge and its EJs.

5. ***Verification and Validation Stage:*** In this stage the model is applied to real life cases, with the results compared to actual data collected from visual inspections conducted during the clarification stage, in order to determine the model's confidence level.

1.6 THESIS LAYOUT

The thesis is composed of five chapters with the content of each of these chapters described below (Figure 1-6):

Figure 1-6 Thesis layout

Chapter 1 gives an introduction on bridge management system, the problem definition, along with research objectives and methodology.

Chapter 2 presents the reviewed literature in the field of Bridge Management Systems, deterioration models and cost analysis.

Chapter 3 presents the methodology adopted in the research and the approaches used to develop a model for expansion joint management.

Chapter 4 highlights the model development, verification, and validation stages by assessing EJ and predicting their condition at various times throughout their lifetime. Moreover, these results are compared to real life case studies.

Chapter 5 presents the research conclusions, as well as highlights recommendations for future research.

CHAPTER 2

LITERATURE REVIEW

CHAPTER 2
LITERATURE REVIEW

Expansion joints EJs are non-structural elements designed to accommodate the bridge deck movement that is caused due to shrinkage, creep, dead and live loads, wind and seismic loads, as well as structural settlements (D'Souza, 2014). In addition, they provide comfort and prevent water runoff and thawing chemicals from leaking through bearings and other elements underneath the deck (WSDOT, 2016). EJs failure thus affects the safety of bridges, and can lead to the deterioration of other structural bridge elements. Thus, it is essential to maintain the conditions of these EJs to prevent the negative impact that their deterioration can cause to civilians and vehicles.

Furthermore, selecting inadequate and/or inappropriate EJs can lead to a higher initial material cost, as well as an increase in bridge's maintenance cost and consequently increase in the lifecycle cost of the structure.

This chapter reviews the literature on EJs showing their different types, reasons for their failure, ways to improve joints performance, maintenance and rehabilitation of joints, factors affecting joints condition, and former studies on bridge management systems.

2.1 TYPES OF EXPANSION JOINTS

There are three types of joints that are categorized according to movement range as shown in Table 2.1.

Table 2.1 Expansion joint movement classification (WSDOT,2016)

Joint Classification	Movement range
Small movement Joint	~ 0.5” – 2” (13 mm – 5 cm)
Medium movement Joint	~ 2” – 4” (5cm – 10 cm)
Large movement Joint	~ >4” (>10 cm)

2.1.1 SMALL MOVEMENT JOINTS

Small movements are capable of accommodating a motion range of up to 50 mm. There are 2 types of small movement joints:

- ***<u>Compression seals (CS)</u>*** are elastomeric sections with an extruded internal web. They are installed within the joint gap in order to seal it against water invasion (Figure 2-1 through Figure 2-4). They are kept in place through the use of friction against the adjacent joint faces, while the seal is kept in a compression state through the use of a lubricant adhesive (Dornsife, 2000). These seals must be installed against a smooth surface. If the concrete finish can offer such a surface then this can be used, however if this cannot be accomplished, then a steel angle is used to provide the required smooth surface that enables installation. Moreover, polymer concrete is used to afford impact resistance. Compression joints allow for movements of up to 50 mm providing uniform compression in the process without bulging out of the joint opening, which provides a smooth passage for vehicles through this joint despite the deck being under compression. The (CS) joint is composed of a neoprene seal which is held in place through the friction exerted by faces of the joint. Moreover, this type of joint is popular due to its cost efficiency and ease of construction execution, (WSDOT, 2016).

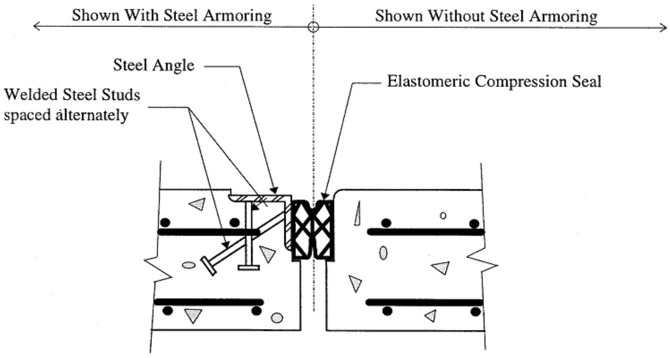


Figure 2-1 Schematic of a compression seal joint (Dornsife, 2000)

Figure 2-2 Compression seal 1

Figure 2-3 Compression seal 2

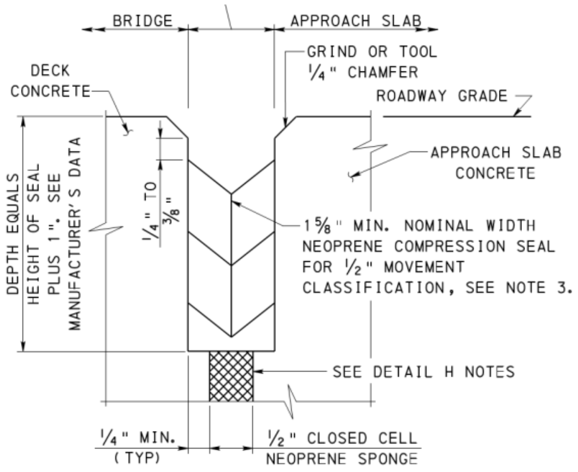


Figure 2-4 Schematic of compression Seal (Dornsife, 2000)

- ***Asphalt Plug Joints*** (APJ) is a Polymer Modified Asphaltic (PMA) joint (Figure 2-5). It is composed of a liquid polymer binder together with graded aggregates that are compacted in block-outs. They accommodate movement of up to 2 inches (51 mm). These joints can be used in both concrete and asphalt surfaces (Dornsife, 2000). Moreover, their construction execution is efficient, while allowing for thermal movement, waterproofing and self-sealing of the joint (WSDOT, 2016).

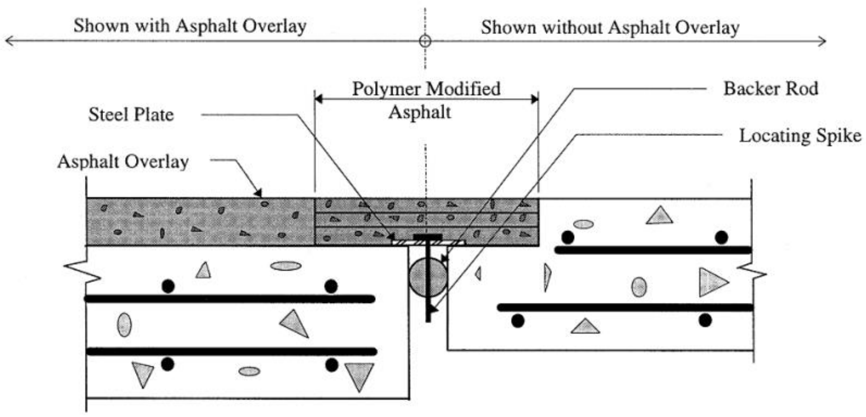


Figure 2-5 Schematic of the asphaltic plug joint (Dornsife, 2000).

According to Johnson (1993), a survey of 250 joints on United Kingdom highway bridges took place and indicated that 50% of bridge EJs were Asphalt plug joints. Moreover, of the surveyed asphalt joints, 50% were leaking and cracking was common, especially in heavily trafficked nearside lanes. Cracking and de-bonding were found more on roads carrying lower traffic loads, particularly in winter.

Marques (2009) conducted an inspection survey of 150 EJs in Brisa, Portugal, these joints included: reinforced elastomeric cushion joints (51%), elastomeric flexible strips (22%), and asphaltic plug joints (9%). Asphalt plug joints were very suitable for small ranges of movement, particularly replacing joints in older bridges. For bridges older than 25 years, about 28% of the bridges have been installed by asphalt plug joints.

2.1.2 MEDIUM MOVEMENT JOINTS

Medium Movement Joints can be used to accommodate a movement range between 50 to 100mm. These joints can be either steel sliding plates or strip seals as described below:

- ***Strip Seal Joints*** are an elastomeric strip seal EJ that consists of a pre-formed elastomeric gland which is mechanically locked into edge rails embedded into the concrete at the side of the joint gap, with the movement being accommodated by the elastomeric gland (Figure 2-6). They are fixed to the deck using steel studs or reinforcing bars that are welded to the edge rails in order to facilitate bonding within the concrete. The main factors affecting their performance are their design and the applied lubricant-adhesive (Dornsife, 2000). The main function of these seal joints is allowing movement as well as protecting the elastomeric gland. Movement is permitted through the elastomeric strip seal that is located between two extruded steel shapes. Moreover, it protects the elastomeric gland from vehicular wear. These joints are composed of a steel extrusion, strip seal and anchorage studs. Based on its mechanism, their performance is directly related to the strip seal strength, integrity of joint edges and anchorage of extrusion.

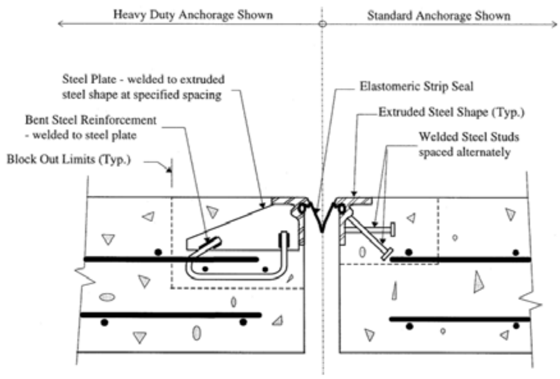


Figure 2-6 Schematic of a Strip Seal Joint (Dornsife, 2000)

- ***Finger Joints*** are fabricated from steel plates and installed in a prop cantilever state (Figure 2-7 and Figure 2-8). They accommodate large movements. These joints are designed to carry traffic loads with stiffness in order to impede vibrations. Nonetheless, they do not offer a water seal, thus an elastomeric is used to redirect water in order to shelter structural elements (Dornsife, 2000).

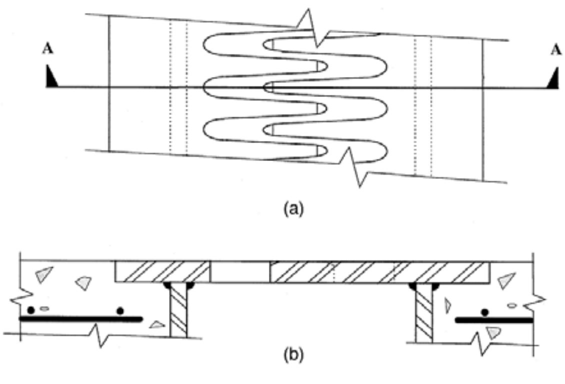


Figure 2-7 Schematic of Steel Finger Joint (Dornsife, 2000)

Figure 2-8 Finger joint

- ***Sliding Plate Joints*** are used as EJs in concrete and timber bridges (Figure 2-9). These types of joints are created through two steel plates that are attached to the deck at each side of the joint opening. These plates are installed while ensuring that their top surface is flush with the top of the deck. Furthermore, these plates are bolted to timber panels or embedded via steel anchorages into the concrete deck. The width of the Steel plate must accommodate the total expected movement. Moreover, the thickness of the plate is determined based on structural requirements (Dornsife, 2000). To ensure that these plates are protected against corrosion, Sliding Plates are galvanized (WSDOT, 2016).

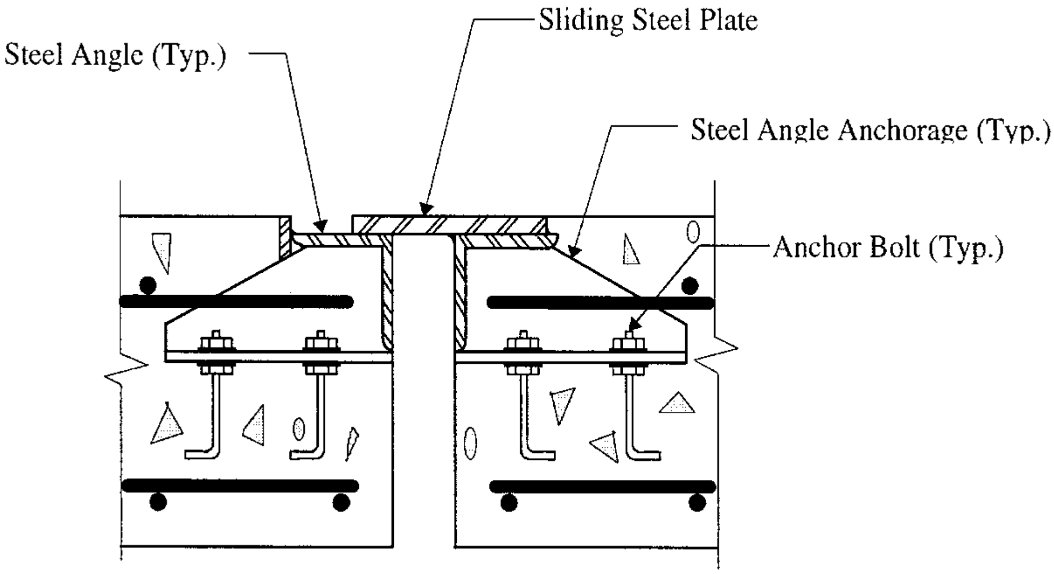


Figure 2-9 Schematic of Sliding plate Joint (Dornsife, 2000)

2.1.3 LARGE MOVEMENT JOINTS

Large Movement Joints are primarily used to provide support across expansion voids, as well as accommodating movement that exceed 100 mm (WSDOT, 2016). An example of these types of joints is the Modular Bridge Expansion Joints (MBEJ). They are complex structural systems that are designed to provide watertight load transfer across joint openings **(**Figure 2-10 and Figure 2-11**).** They were developed in Europe and introduced in the US during the 1960s. Moreover, these joints are shipped to construction sites in an assembled configuration. MBEJs have center beams supported on support bars. They are arranged parallel to joint axis, while the support bars are parallel to the primary direction of movement. They are classified into either single-support or multiple-support bar systems. In the case of the multiple-support system, each center beam is carried by a single support (Dornsife, 2000).

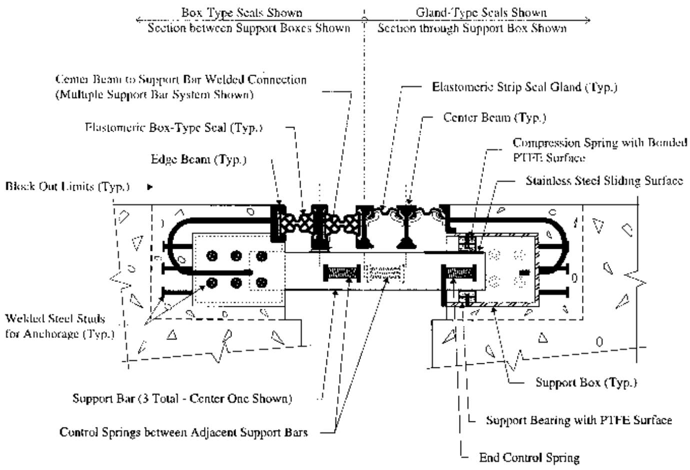


Figure 2-10: Schematic of modular bridge expansion Joint (Dornsife, 2000)

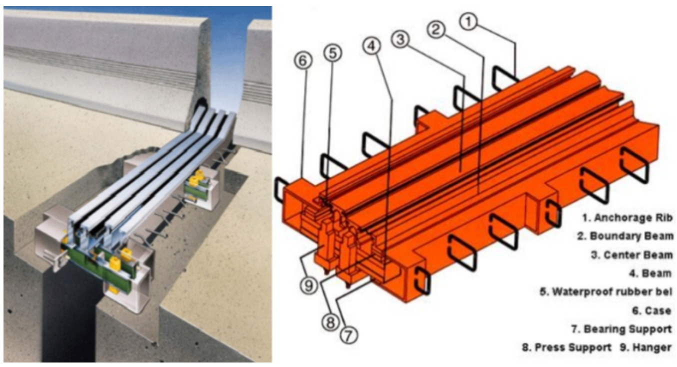


Figure 2-11 Modular bridge expansion joint (Wuxi, 2017)

2.2 REASONS OF JOINTS FAILURE

There are a number of reasons that can be attributed to the failure of joints. Below is an overview of some of the main reasons for such failures:

- Unsuitable Installation
- Excessive water
- Unconsidered movement in the design
- Unfastened bonds
- Failure of material
- Improper alignment

- Descent of deck
- Creep or shrinkage
- Traffic

2.3 IMPROVING JOINTS PERFORMANCE

The National Corporative Highway Research Programs (2003) proposed several suggestions listed below to improve joints performance in order to extend their lifespan. These include:

1. Applying an active maintenance program.
2. Implementing joint block-outs next to openings during the placement.
3. Backing the joint system replacement by concrete.
4. Placing seals that match with the surrounding temperature.
5. Ensuring that the opening size is properly assembled.
6. Placing the joints after overlay placement.
7. Protecting infrequent movement that damages the seal.
8. Following the suggestions of the manufacturer during joint selection process.
9. Excluding splices in pre-molded expansion materials.

2.4 MAINTENANCE AND REHABILITATION OF JOINTS

This section describes four processes that must be applied to ensure the prolonged lifetime of the bridge; consistent maintenance, preventative maintenance, repair and rehabilitation (Table 2.2).

- ***<u>Consistent maintenance</u>*** is carried out at predefined intervals. This type of maintenance is used to for a number of purposes, including but not limited to; cleaning of joints, drainage systems, carriageways, steel railings protection, lighting columns and safety barriers. The scope of such maintenance as well as the time needed for such works is pre-determined, based on the bridge's structure type and equipment. While regular scheduled maintenance is required, in the event that the inspection highlights that the element is in a satisfactory condition, then the scheduled maintenance can be deferred.

- ***Preventative maintenance*** is carried out to delay deterioration. In most cases, it is linked to delaying the corrosion of structural steelwork. Preventative maintenance repairs include maintenance for; drainage system defects and/or replacement of such systems, surface coatings application, steelwork application, EJs renewal and crack sealing.

- ***Repair*** is a restoration process that aims to return damaged elements to their original condition.

- ***Rehabilitation*** involves the restoration of joint serviceability due to its original condition after deterioration has taken place. Its purpose is to regain the original capacity of joints.

Table 2.2 Rehabilitation options and actions (Stewart, 1996)

Rehabilitation	***Activity***
Maintenance	*Cleaning deck 2 times/week at least or cleaning debris*
Repair to good condition from medium condition	*Recasting concrete around joints or replacing them*
Repair to medium condition from fair condition	*Re-casting concrete around joints and re-fixing them*
Replacement	*Re-casting concrete around a joint and replacing it totally*

Repairing of joints is a crucial activity that needs to be routinely undertaken to prolong the joints' lifespan. Repairing is divided into two activities:

1. Repairing to reach a good condition from a previously medium condition.
2. Repairing to reach a medium condition from a previously fair condition.

It is essential to ensure that maintenance and rehabilitation is undertaken periodically as to prolong the lifespan of the joints. In the event that this is not undertaken, the joints will deteriorate rapidly, and require replacement. In the event that a joint needs to be replaced, this will result in a higher cost since the joint will need to be removed and replaced by another, while concrete will need to be recast.

2.5 FACTORS AFFECTING JOINTS CONDITION

Many factors affect joint condition. These factors are classified into 5 groups; forces, loading, structure, design and construction (Reynolds, 1972):

- ***Forces:*** Includes; rain, sun, snow, carbon dioxide, dust, temperature and moisture.
- ***Loading:*** Includes; traffic density and loading (live traffic load movements as well as their associated vibrations).
- ***Structure:*** Includes; camber growth, components fatigue, lateral movement (i.e. tilting or movement), abutment or slab settlement, shrinkage, creep, deflection, rotation, bearings displacement and impedance of anchorage systems
- ***Design:*** Includes; improper design, improper joint type or material selection, poor drainage, ineffective waterproofing, insufficient clearance, limited maintenance, difficulties of repair or cleaning, improper mix preparation, poor design, unplanned for movements, incorrect bearing

location, incorrect modulus of elasticity, different expansion coefficients of concrete, exothermic epoxy during curing, skewed structures and lack of detailed drawings.

- ***Construction:*** Includes; poor installation, inappropriate temperature, inadequate site preparation, poor workmanship, inadequate bedding, bond or anchorage, failure of fixings, looseness, poor vertical or horizontal alignment, improper construction of gaps and seal punctures.

In assessing the condition of EJs, several of their characteristics have to be examined. These characteristics include (Lee, 2005):

- Lodge structure movements in the vertical and horizontal directions.
- Endure applied loads.
- Provide a blameless riding quality without inconvenience or hazards.
- Does not induce vibrations during operation.
- Endure chemicals attack.
- Require little or no maintenance.
- Allow stress-free inspection or replacement.

It is important to define a number of important terms and concepts that commonly used in bridges management systems' studies. Below is a list of such major definitions:

- ***Condition Rating*** is a rating which compares an element's current state to that of its original condition (Hartle et al., 2002).
- ***Visual Inspection*** is the rating of components based on the inspector's experience, symptom or damage, and defect level (Hartle et al., 2002).

- ***Condition Rating Index*** is a sign of the material state at a specified time (Wang & Hu, 2006).

2.6 FORMER STUDIES ON MANAGEMENT PRACTICES FOR BRIDGES AND EXPANSION JOINTS

Extensive studies have been conducted globally concerning developing bridge management systems. These studies can be primarily classified under three commonly used methods:

1. Condition assessment models
2. Deterioration prediction models
3. Optimization models

2.6.1 CONDITION ASSESSMENT MODELS

There are many aspects and modules developed to assess the condition of structures and elements. Choosing the appropriate module to predict the condition of elements is based on the given data. Fuzzy logic (FL) and artificial neural networks (ANN) are considered the major modules for assessing the condition of element and they will be discussed in the following paragraphs.

Fuzzy Logic

Fuzzy Inference System uses a set of rules based on fuzzy sets in order to profile a basis for the model's estimation (Baldwin, 1981). In order to create such a model the system should identify fuzzy inputs as well as presenting their outputs, create fuzzy membership-functions for every rule base and decide how the activity is performed. The fuzzy inference process is achieved in four steps; fuzzification, rule evaluation, aggregation and defuzzification (Tarighat and Miyamoto, 2009).

- ***Fuzzification*** is to crisp the inputs and determine the belonging level to fuzzy sets.
- **Rule evaluation** is to use the inputs and relate them to fuzzy rules experiences.
- ***Aggregation*** is the output unification of rules.
- ***Defuzzification*** input is the aggregate output of the fuzzy set and is provided as a single value (Esragh and Mamdani, 1981).

(FL) Studies attempts to model the uncertainty associated with describing an event in fuzzy language, or natural linguistic descriptive language. This logic enables modeling and building upon uncertain events and observations. Moreover, (FL) and fuzzy mathematics can be used to model bridge assessment (S. Sasmal, 2006), with a number of extensive research conducted in this field.

Zhao and Chen (2001) presented a knowledge-based system for bridge damage diagnosis that aims to provide bridge designers with valuable information about the impacts of design factors on bridge deterioration. (FL) was utilized to handle the uncertainty and imprecision in the system. The study developed a practical assessment tool for diagnosing and modeling deterioration of concrete bridges.

Furthermore, Kawamura and Miyamoto (2003) presented an approach for developing a rating system for concrete bridge deteriorated. The model is based on evaluating the performance of concrete through visual inspections and technical specifications. Moreover, a survey of experts was conducted in order to establish the knowledge base for the fuzzy model.

Yousheng and Hani (2005) developed a fuzzy model of two fuzzy membership functions (trapezoidal and step-wise) in order to monitor bridge health. The model used data extracted from the electronic bridge database of Kansas

Department of Transportation (KDOT) which is used by PONTIS (FHWA, 2008). The study concluded that predicted health of the bridge marginally deviated from the actually conditions, thus reflected the advantage of using (FL) for such an application.

Additionally, Rudolf (2007) developed a fuzzy interference system model that provides technical condition evaluation of railway bridges. The model was validated based on data from actual bridges that are in operation. The study recommended collecting data regarding the technical conditions of brides using an inspection form that was designed in the study.

Saptarshi (2008) developed a systematic procedure for condition evaluation of existing bridges using an analytic hierarchy process in a fuzzy environment. The produced model helps in forecasting the condition of the bridge elements, thus helping in providing priority regarding the order in which these elements need to be repaired.

Moreover, Tarighat and Miyamoto (2009) introduced a new fuzzy model to rate the bridge deck condition based on both subjective and objective results of existing inspection methods and tools. The developed model was based on five input factors; spalling, crack width, delamination, hammer tapping and corrosion, with the model providing the bridge deck fuzzy condition rating as its output. In order to provide such results, the model used a set of 162 rules between input data, providing equal weights among each of the rules. The condition rating transformed the qualitative descriptions of: Excellent, Very Good, Satisfactory, Fair, Poor, Critical and Failed, into a quantitative rating from 1-7 according to FHWA (1995). The research divided the concrete bridge deck into two elements; Slabs and Girders. Moreover, the model was tested and verified by comparing its output to bridge deck condition data retrieved from FHWA (1995). The results presented minor deviations and data noise compared to the actual conditions, highlighting the accuracy of the model.

Degrauwe et al. (2009) presented a methodology based on fuzzy numbers to investigate the propagation of measurement errors and uncertainty on structural temperature throughout the updating of procedure of loads during the execution of cable stayed bridges. The analysis shows that for most cables, frequency change can be determined through the temperature difference between two measurement dates and the force redistribution effects of the cables.

Furthermore, Pan et al. (2009) presented a multiple fuzzy linear regression model using matrix algebra. The model is capable of handling a mixture of fuzzy and crisp data. The model is capable of providing future conditions of the bridge, which can assist bridge operators and managers their decision making process and establishing better maintenance plans.

Malekly et al. (2010) developed a systematic decision model to select the best highway bridge design idea. The rating values regarding each alternative are described in a fuzzy environment by means of linguistic variables.

Yunjie et al. (2010) developed a fuzzy comprehensive expert system for assessing damage of in-service bridges. The system considered the bridge service life and loads as inputs to the model. The model could be used to evaluate the damage to in-service concrete bridges, and determine the maintenance and strengthening schemes for these bridges.

Lin (2012) presented a fuzzy regression approach for the assessment of the potential vulnerability of bridge to earthquakes. Fuzzy regression is adopted to synthesize the maximum displacement of the bridge sections under such dynamic loads and to develop a bridge alert-action principle.

Moreover, Ling et al. (2013) designed and fabricated a six bay truss model and conducted a series of experiments on the model in order to reflect real life deterioration of bridges due to various factors. The research simulated the damage by loosening the bolts of joints and introducing environmental variability by changing the shaker's input level. A fuzzy clustering model was conducted using the model data, with the results highlighting that the model accurately represents the practical effect of environmental factors and conditions on bridges.

Additionally, Ardeshir et al. (2014) conducted a study to rank potential river bridge construction sites using a fuzzy analytic hierarchy process. The model suggests bridge locations through the use of GIS with these sites filtered according to the length and height of each bridge at each potential location.

In addition to maintenance and repair, (FL) has been used to estimate the cost of conceptual designs of bridges as presented in the research conducted by Markiz and Jrade (2014). The research focused on box girder bridges, taking into consideration site preparation, substructure and superstructure systems.

Jiao et al., (2014) developed a fuzzy neural network-based damage assessment model for bridges under temperature change effect. The research assumes a uniform load surface curvature as a damage indicator as well as Modulus of Elasticity of concreting being temperature dependent. The study reveals that the model can effectively identify the damage condition caused by temperature change.

Finally, Dinh et al. (2016) developed a model that helps transportation agencies communicate the condition of bridges internally. The model can be used along with other performance measures, for planning deck maintenance activities for individual bridges or a network of bridges. The model is also used to rank bridge deck maintenance projects according to maintenance priority.

To sum up, Fuzzy inference systems have been widely used to assess and predict the conditions of bridges elements while no previous research was carried out using fuzzy logic in estimating bridges EJ conditions. As a result, a fuzzy inference module will be developed to predict bridges EJ conditions, with the findings of this model compared to the actual condition of the bridges based on visual inspections.

Artificial Neural Network

ANN is a computer practice that attempt to simulate the thinking process of the human brain. Intelligence is considered as the activity of neural networks procedure. The learning mechanisms in neural networks exist to obtain the knowledge. The structural model of neural networks has been considered as various types based on their training activities. The neural networks are able to model the non-linear relationship between a set of input variables and their outputs without the need to define any other relationships between them. (Jaeho et al., 2005)

The main advantage of ANN is that it is able to control many inputs and efficiently categorize different objects. The ANN model process mainly consists of two steps, training and testing. It is required to varying the network's weights during the training process to be able to perform specific tasks using neural networks. The calculation of this process is an error deviation of the weights between the desired output and actual output. (Suryanita & Azlan, 2013)

Jaeho et al. (2005) developed an ANN model that determines the condition rating of bridges by predicting the time series data of bridge elements. The model aims to overcome insufficient historical data problem. The model considered all the bridge elements “deck, expansion joints, piers, ties, beams…etc.”. five hundred and twenty eight processing elements are used for training while one hundred ninety eight are used for testing. The results showed a big deviation between actual and generated results in year 10. This deviation decreased in year 11 which means that this deviation can be minimized by increasing the size of training sets.

Bouabaz and Hamami (2008) focused on developing a cost estimation model for M&R of bridges in developing countries using ANN. The model is able to estimate the M&R cost based on initial cost and design parameters collected from 40 projects. 32 projects were used in training the model while eight projects were used for model testing and validating. The model results showed only 4% deviation between estimated value and bill value.

Suryanita & Azlan (2013) developed an ANN model that is able to predict the condition of bridges condition given the earthquakes parameters; acceleration and displacement. The model would guide authorities to repair or maintain the bridges as early as possible before the bridge was damaged. One thousand eight hundred and nine data was collected through four earthquakes. 70% of data was used for model feeding and training; 30% are used for model testing and validating. The output of the ANN is compared to the output of regressions (R-mean). The result shows that ANN model is suitable for predicting the bridge condition.

Asadi et al. (2011) developed a life-cycle cost analysis model using ANN. The model is based on collecting historical data for 14 distributed bridges. The data was analyzed to determine the total life cost for these bridges. The input parameters of the model are length, width, age and the initial price if the bridge and the output is the LCC of the bridge. The 14 bridges generated about 800 sets of data over 60 years. About 60 percent of data were used as an input and output while the rest was used for testing and verification of the model.

Fuzzy logic (FL) assists in making certain decisions based on ranged or indefinite data, while ANN attempts to simulate the human thinking procedure to solve problems without modeling them mathematically. Despite the fact both of these approaches can be used to solve nonlinear problems, they are not related. Contrary to FL, ANN tries to apply the thinking process in the human brain to solve problems. Further, ANN includes learning and training process that involves learning algorithms and requires extra training data (Indika, 2011).

2.6.2 DETERIORATION PREDICTION MODELS

Deterioration modeling is a procedure to determine the performance loss, and is important for assessing the lifecycle and maintenance requirements of bridges. Deterioration can be defined as a change where transition depends on maintenance plan (Garavaglia et al. 2004). According to Cesare at al. (1992) it is preferred to model deterioration probabilistically rather than deterministically, through assessment of potential traffic loads and environmental conditions. The probabilistic model is advantageous due to its capability of providing projected results beyond limits of the input data provided to the model.

Butt et al. (1987) established one of the earliest probabilistic models in bridge performance evaluation, in which they used the Markov Decision Process (MDP) technique to develop a pavement performance model. The pavement condition matrices were attained by minimizing pavement conditions at a precise time.

Moreover, Scherer (1994) explored the use of (MC) models in the performance assessment of Virginia bridges. The results of the research indicated that (MDP) is a powerful technique for bridge management. In addition, (MC) Modeling is based on assuming that conditions are described by "condition states". The Markov approach entails that the probability of deterioration is solely dependent on the previous condition state of the element, and not the element's entire deterioration history.

2.6.3 OPTIMIZATION MODELING

Genetic Algorithm (GA) generate solutions to optimization problems by implementing techniques such as: mutation, inheritance and selection, which attempt to mimic the evolution process. Whitley (1994) defined GA as computational models inspired by evolution. These algorithms convert potential solutions to specific problems, and are viewed as function optimizers, Figure 2-12.

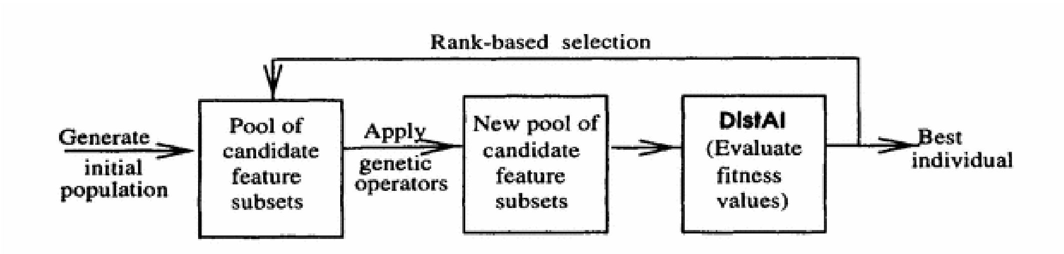


Figure 2-12 Genetic Algorithm Procedure (Whitley, 1994)

Miyamoto et al. (2000) developed an optimization model using (GA) for deteriorated concrete bridges by assessing the results retrieved from a bridge rating system. The developed model introduced numerous maintenance plans by targeting minimum maintenance cost and maximum condition index (CI). The developed model was able to estimate the deterioration of the bridge members. Liu and Frangopol (2005) developed a model that aims to reach the optimum maintenance plan for bridges. The model used (GA) as a search engine to find out the best maintenance scenario from a large pool of maintenance plans by combining both safety and life-cycle cost

Aydın and Ayvaz (2013) developed a model for precast pre-stressed I shape beams cost optimization. The model took into account the cost of the pre-stressed concrete, deck concrete, pre-stressed I-beam steel, deck reinforcing steel, and formwork. In 2016, Majid S. et al. developed a computer-automated design model based on (GA) to optimize concrete slab frame bridges targeting the reduction in the investment cost. The model parameters included necessary reinforcement diagrams and fatigue checks for the whole bridge. A case study was done comparing the optimized bridge results with a previously constructed bridge and the results showed substantial potential savings in matter of materials and costs.

2.7 SUMMARY

The studies of bridge systems, their performance evaluation and their maintenance, repair and rehabilitation process, presented in this Chapter, illustrate that:

- (FL) assessment modeling could be used to evaluate the condition and health of bridge elements in case of lack of data and maintenance history.
- Probabilistic deterioration technique models like Markov model provide accurate technique for modeling bridge management systems. However, no deterioration models were developed particularly for EJ.

- (GA) can be used as an optimization technique in order to determine the optimum maintenance and repair plans for EJs.
- Limited research was conducted to assess and predict the condition of EJs.

CHAPTER 3
RESEARCH METHODOLOGY

CHAPTER 3

RESEARCH METHODOLOGY

This chapter highlights the methodology adopted in this research. It starts with illustrating the scope and objectives of the model development, and then continues in describing the adopted methodology. The need for establishing an expansion joint management system (EJMS) is discussed along with the different modules developed to form the full integrated system.

3.1 INTRODUCTION

The idea of this research was inspired mainly because of the deteriorated condition of bridge EJs in Egypt which interprets the traffic flow, leading to waste of energy and time for passengers and on the business level. The research began with the aim of applying efficient EJMS for Egyptian bridge network. Nonetheless, due to the lack of available information regarding the maintenance history of EJs in Egypt, this goal was found to be unattainable. However, this lack of information formed the inspiration for developing a model that can predict the current and future EJs condition, in addition to recommend optimized strategy for repair and maintenance work. The developed model presents an integrated framework between various tools and methods.

In order to develop such a model, extensive literature review has been undertaken regarding each of the following:

1. Different types of EJs used in Egyptian bridge network.
2. Condition assessment application
3. Factors affecting the condition and behavior of EJs

4. Asset management modules for expansion joints EJ: asset inventory and inspection, condition rating systems, deterioration models, and maintenance strategies.
5. Applying Optimization algorithms on bridge EJ management systems for M&R strategies.

In Egypt, with the pressing population and high traffic densities, a simple EJ failure would disrupt the complete traffic flow over the bridge leading to waste of time and money. This shaped a pressing need to search for the causes and effects of EJ failure beside the history about their maintenance and repair. Figure 3-1 shows that the research passed through several stages.

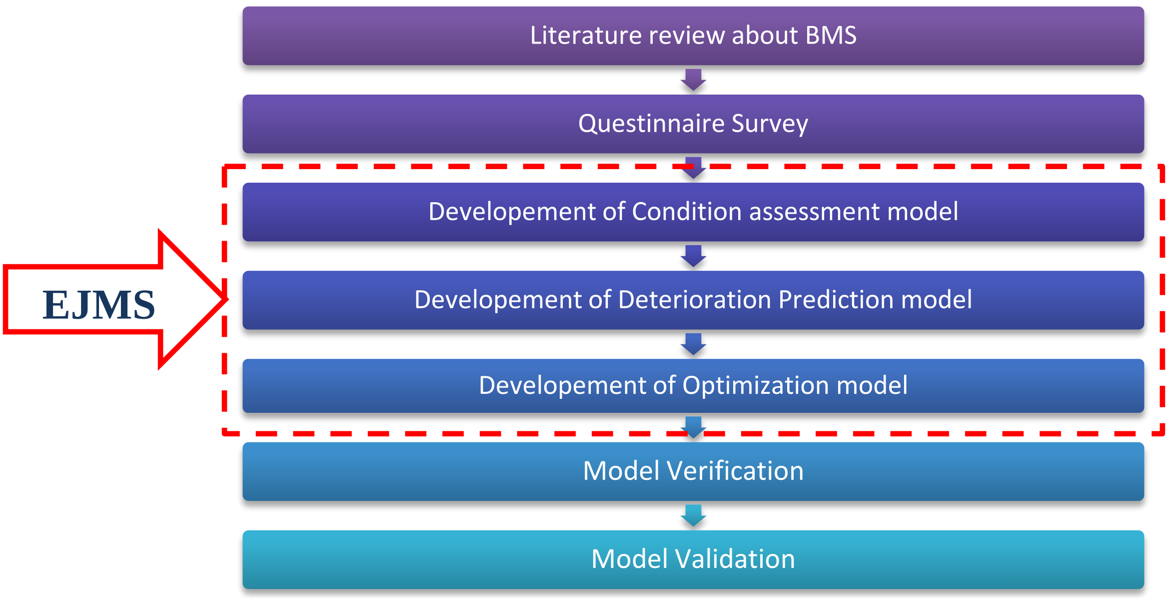


Figure 3-1: Research Methodology development phases

Lack of information related to maintenance and repair history was one of the main reasons to drive the researcher focus towards the need to predict the condition of EJs.

In order to assess the condition of EJs, it is imperative to gain a better understanding regarding the factors that affect the EJs condition. Accordingly, a questionnaire (Appendix 1) was used to compile data related to the factors affecting the condition of EJs in Egypt.

Visual inspections and assessment of expansion joints were conducted. The information obtained through the visual inspections and assessment forms the benchmark for verifying and validating the final output of the condition assessment model, with the model capable of predicting conditions for a period of up to 10 years. Moreover, an optimization process was developed in order to produce an optimum transition matrix for thermal EJs and support decision makers to select the optimum strategy for maintenance and repair for bridges EJs.

3.2 EJMS MODEL DEVELOPMENT

The flow chart shown in Figure 3-2 presents the model development. It presents each of the steps undertaken, as well as the tools used in each of these steps.

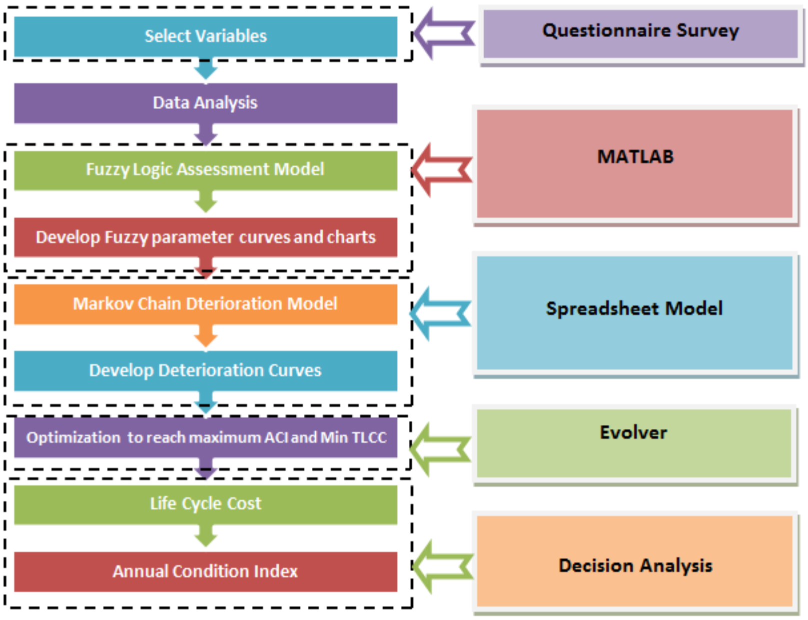


Figure 3-2 EJMS Model Development

3.2.1 QUESTIONNAIRE PHASE

Due to the lack of information regarding factors that affect the joint condition, a questionnaire was used and distributed to experts in the Egyptian bridge industry. The aim of the questionnaire is to capture the opinion of experts regarding the factors affecting the condition of EJs in Egypt.

The questionnaire was sent to 120 bridge experts in Egypt, including owners, consultants and contractors. Seventy-five responses were received presenting a 62.5% response rate. As shown in Figure 3-3, the responses included:

- 11 bridge owners
- 23 consultants
- 41 contractors that carry out EJ inspections

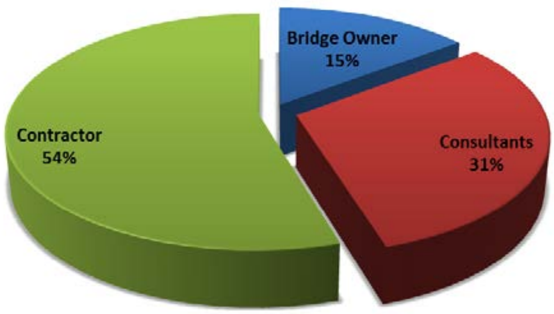


Figure 3-3 Responses Received for the Questionnaire

The collected data from the 75 questionnaire was filtered and analyzed by calculating the arithmetic means for each question. This was used in developing the condition assessment Model. The obtained data was sorted in tables and was used as input to feed the model.

Table 3.1 through Table 3.5 present the response received for each of the questions posed to the experts in the questionnaire. The majority of the experts defined a new bridge as having an age of four or less years, with medium ranging from two to eight years, with old bridge as being older than seven years. Moreover, ADT of less than 1000 is defined as low traffic, with 800-3000 describing medium traffic flow, and greater than 2500 describing high traffic flow.

Since experts were requested to provide to translate qualitative measures into quantitative values, it is important to find a mean to compile this information due to the varying perspectives of each expert. In addition and due to vagueness and absence of sharp cutoff points as there is no finite number of truth values, fuzzy logic (FL) was used, as recommended by (Krinninger, 2014), in order to assess the condition of EJs according to the data collected from the questionnaire.

Table 3.1 Feedback of EJ age

Questionnaire choice	*New*	*Medium*	*Old*
B	*0-4*	*2-8*	*More than 7*

Table 3.2 Feedback of Average Daily Traffic

Questionnaire choice	*Low*	*Medium*	*High*
B	*0-1000*	*800-3000*	*More than 2500*

Table 3.3 Feedback of joints in new bridges under temperature and traffic changes

Temperature / *Traffic*	*Cold*	*Warm*	*Hot*
High	*fair*	*fair*	*fair*
Medium	*good*	*good*	*fair*
Low	*good*	*good*	*good*

Table 3.4 Feedback of joints in medium aged bridges under temperature and traffic changes

Temperature / *Traffic*	*Cold*	*Warm*	*Hot*
High	*fair*	*fair*	*Poor*
Medium	*fair*	*fair*	*fair*
Low	*fair*	*good*	*fair*

Table 3.5 Feedback of joints in Old bridges under temperature and traffic changes

Temperature / *Traffic*	*Cold*	*Warm*	*Hot*
High	*Poor*	*Poor*	*Poor*
Medium	*Poor*	*Poor*	*Poor*
Low	*fair*	*fair*	*fair*

3.2.2 CONDITION ASSESSMENT MODEL

Based on National Cooperative Highway Research Program NCHRP (2003), it was also inferred that there are many factors affecting the joint condition, which include the following primary contributors:

1. Movement range
2. Joint age
3. Bridge span
4. Type of bridge
5. Joint type
6. Average Daily traffic (ADT)
7. Maintenance
8. Bridge alignment
9. Temperature

Nonetheless, while each of these factors listed above contributes to the joint condition index, it was found that the factors not affected by human involvement are:

1. Expansion joint age
2. Temperature
3. ADT

According to Abu-Samra, Zayed et al., 2017, the main criteria to rate the condition of pavement, which has similar characteristics of thermal joints, are climate conditions, physical properties, and operational factors. They categorized these criteria into 3 sub-criteria (air temperature, pavement age, ADT). Accordingly, this research is focusing on these three main factors.

The questionnaire as well played an important role in reaching the values for the membership functions used in the FL model.

- ***Membership Functions:*** In order to predict the joint condition, membership functions influencing the joint performance should be identified and incorporated in the assessment model. The factors influencing joint performance that were used in the model were; temperature, age and average daily traffic as shown above. A description of each of these factors is shown below:
    - ***Temperature*** affects air moisture and the characteristics of joint material, thus affects the overall performance of joints.
    - ***Joint Age*** is an important factor that influences joint performance, where older joints experience more problems. Joint age is measured through subtracting the year of installation from the inspection year.
    - ***Average Daily Traffic (ADT***) is recorded as vehicles per day. It is an important factor since high traffic volumes result in higher levels of damages to the joints.

The output of the fuzzy model results from combining membership functions with the control rules to derive the fuzzy output (condition rating). The input is converted to the different members of the associated membership functions based on its value. Therefore, the output of the condition assessment model is based on the FL membership functions, which can be considered as a range of inputs.

As previously mentioned, there is no data regarding the condition and maintenance history of bridge expansion joint in Egypt. This indicates that engineers are able to identify the current condition of a joint only based on visual inspection; however they are unable to identify its history, which hinders the ability to determine deterioration rates of joints. Furthermore, deterioration rate is a key factor in forecasting future joint condition, thus with the unattainability of this factor, it is important to identify an alternative tool that can aid in conducting such a prediction.

The developed condition assessment model offers the mean for assessing the joint condition based on limited input information. As previously stated the model uses three primary criteria for conducting such an evaluation; age, temperature and traffic load. The model was developed along with its fuzzy rules based on data collected from a survey of 75 bridge experts in Egypt. The distributed questionnaire was designed to quantify the condition of joints, along with possible causes for the current state of the joint. This provides an important benchmark that can serve as a reference in assessing the criteria upon which performance of joints can be assessed.

3.2.3 DETERIORATION PREDICTION MODEL

The condition index deduced from the condition Assessment Model was then integrated with EJ deterioration model that is capable of predicting future condition index of EJs based on probabilistic approach.

The literature review showed that the probabilistic approach is suitable for describing the deterioration behavior of bridge elements. The probabilistic approach applies Markov Chain (MC) technique. This probabilistic approach is preferred for the following reasons (Bu, 2013):

- The uncertainties in the behavior of EJs under variable traffic flows and temperature, etc., which means that the behavior of EJs is probabilistic rather than deterministic.
- The probabilistic approach has the advantage of ensuring that predictions beyond the limits of the data will continue to have the classic pattern of a deteriorating condition with age, while the regression models cannot guarantee it.
- In addition, the MC model is easy which gives a motivation to be integrated into optimization processes.

Therefore, MC models were used to develop the transition probability matrix to formulate the deterioration model in order to predict future condition of expansion joints.

The deterioration model was then integrates with life-cycle cost according to different maintenance plans. This enables the model to estimate the Annual Condition Index (ACI) for joints.

3.2.4 OPTIMIZATION MODEL

An optimization model is developed through the implementation of GA in order to obtain the optimum maintenance plan to meet an annual available budget, which maximizes the annual condition index (ACI) or to meet certain condition index while minimizing the total life cycle cost (TLCC). Transportation agencies anticipate the development of new strategies to manage maintenance plans that ensures sustainability within given limited budgets. This research targets a given budget in order to reflect the real life practice of the industry, in order to ensure that the findings of the study can be used by the required authorities. Moreover, a sensitivity analysis is conducted to find out the relationship between total life cycle cost (TLCC), percentage of failing joints, and average annual condition index.

3.2.5 MODEL VERIFICATION AND VALIDATION

The developed model is applied to real life bridges in order to test and insure that all the developed modules are efficiently and logically integrated to produce sound results. Many visits were performed to these bridges in order to inspect and assess the current condition of the bridges EJ.

Each EJ of the real life bridges was inspected separately by expert engineers to give it a score out of 5 reflecting its current condition. On the other hand, the average daily traffic was calculated by counting the vehicles passing of the expansion joints per day. Moreover, the maximum temperature in the year was retrieved and provided to the model in order to find out the model's calculated condition. The results retrieved from the developed model were compared to data collected from the visual inspections. An example of the bridges visited was "sixth of October bridge", which is considered the longest bridge in Egypt.

The Sixth of October Bridge forms an important artery in Cairo's road network. It spans over 21 km and connects two governorates (Cairo and Giza), with a deck width varying from 3 to 14 meters with a variety of joint types, and employing 23 ramps. Its structural system varies from one location to another, adding to the complexity of the bridge. Its first phase of construction began in 1969 and has continued throughout the 21st Century.

From the field inspection visits by the experts, it was found that 54% of the bridge's joints are thermal joints and 26% of the EJs need replacement (Table 3.6 and Figure 3-4)

Table 3.6 Number of Observations of Joints of Sixth of October Bridge

	Good	***Medium***	***Needs Replacement***	***Total***
Thermal Joint	*181*	*15*	*89*	***285***
Finger Joint	*112*	*9*	*39*	***160***
Asphalt plug joint	*26*	*34*	*21*	***81***
Total	***319***	***58***	***149***	***526***

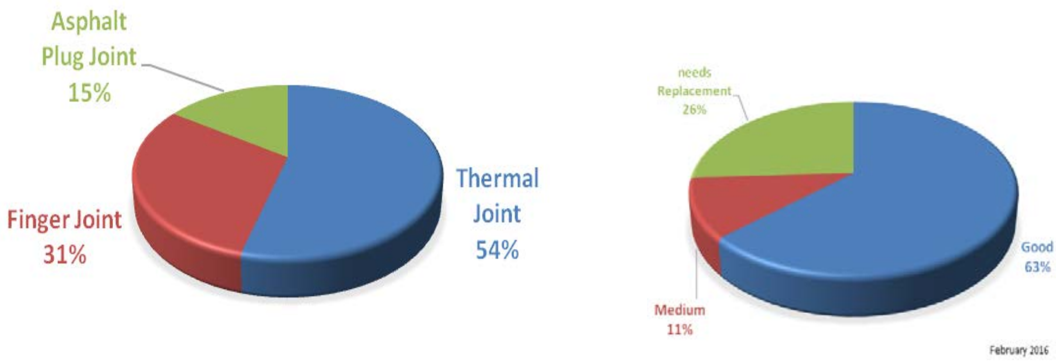


Figure 3-4 Expansion joints types of Sixth of October Bridge

This in addition to the visits to several other bridges and meeting with experts, it was found that the most commonly used type of EJ in Egypt is thermal joints. Accordingly, the performance of this type of joints is critical in the assessment of bridge performances in Egypt and will be taken as the focus of this research.

3.3 SUMMARY

This chapter covers the strategy and methodology that is conducted in performing the research. The chapter also highlights the methods and techniques used for condition assessment, deterioration modeling, repair and maintenance strategy optimization, and how the objective of this research was developed.

Chapter four presents the application of the research methodology, and describes in detail the model development and analysis in the context of the undertaken cases. It shows as well the different stages in model development, and model verification and validation.

CHAPTER 4

EXPANSION JOINT MANAGEMENT SYSTEM (EJMS) – DEVELOPMENT, VERIFICATION AND VALIDATION

CHAPTER 4

EXPANSION JOINT

MANAGEMENT SYSTEM (EJMS) – DEVELOPMENT, VALIDATION AND VERIFICATION

4.1 INTRODUCTION

This Chapter describes the integrated framework which forms the EJMS. EJMS has been constructed with the aim to predict the condition index of expansion joints EJs with a limited amount of input information, and to optimize the maintenance and repair decisions as well. Therefore, it is essential to identify the tools used in EJMS which are capable of overcoming these shortcomings.

4.2 EJMS FRAMEWORK

In this research, and as previously stated, due to the lack of information and history data about EJ maintenance and repair, FL is used to assess the condition of EJs based on data extracted from the questionnaire survey. In addition, MC deterioration module is used to estimate future condition of EJs. An optimization model is also developed to reach optimal maintenance strategies for EJs.

EJMS is composed of several modules that are integrated together, with each module responsible for aiding in the prediction of joint condition, as well as identifying an optimal plan for the maintenance and repair of bridges to support decision makers. These modules include:

- Condition assessment model
- Deterioration prediction model
- Optimization model

These modules are integrated within an overall framework to form the EJMS as shown in Figure 4-1. The sections below describe each of the modules listed above.

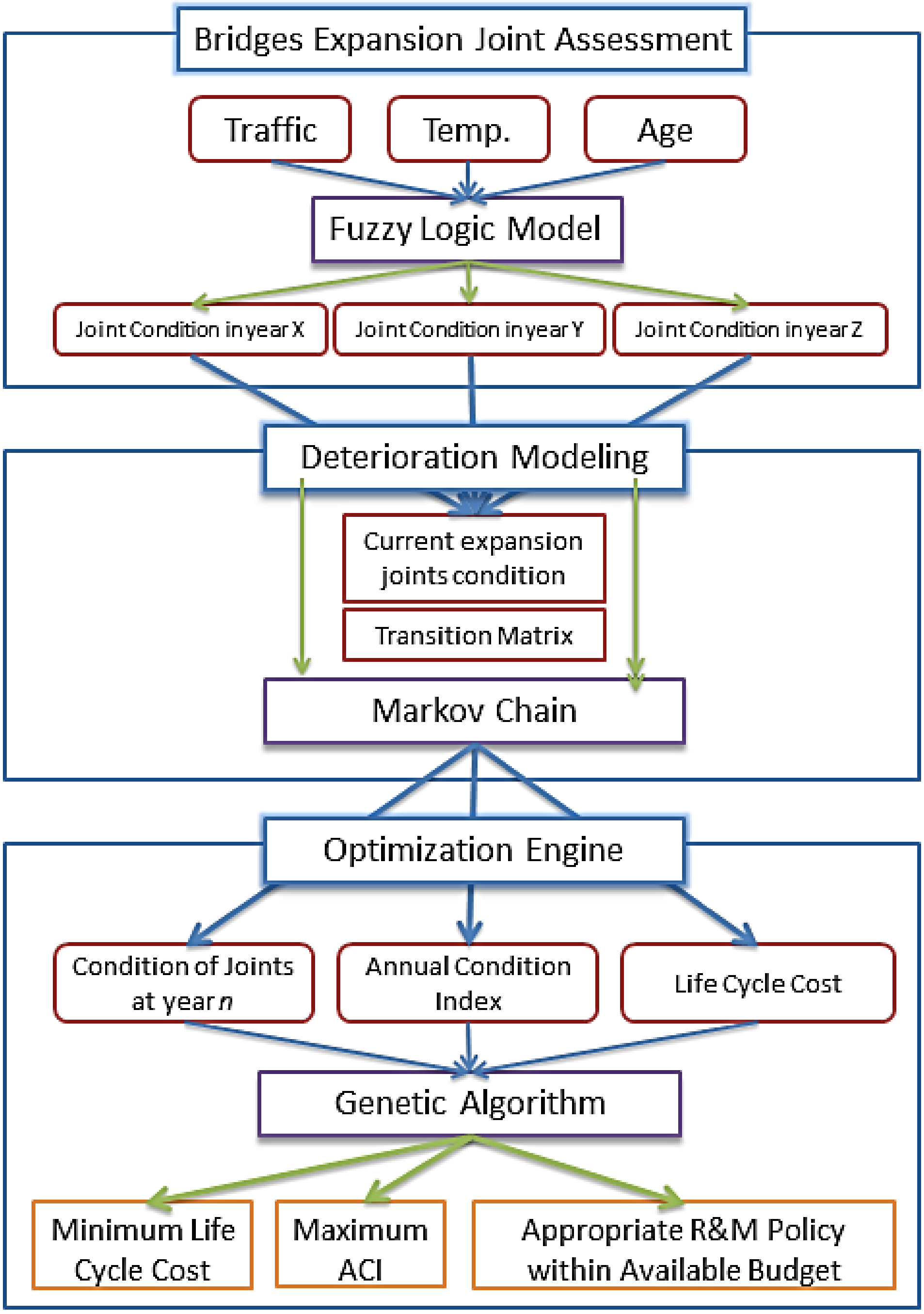


Figure 4-1 EJMS Framework

4.3 CONDITION ASSESSMENT MODEL

Figure 4-2 shows the Fuzzy logic module used for predicting the EJ condition index. It illustrates the membership functions for inputs and output fuzzy condition rating for bridges EJs.

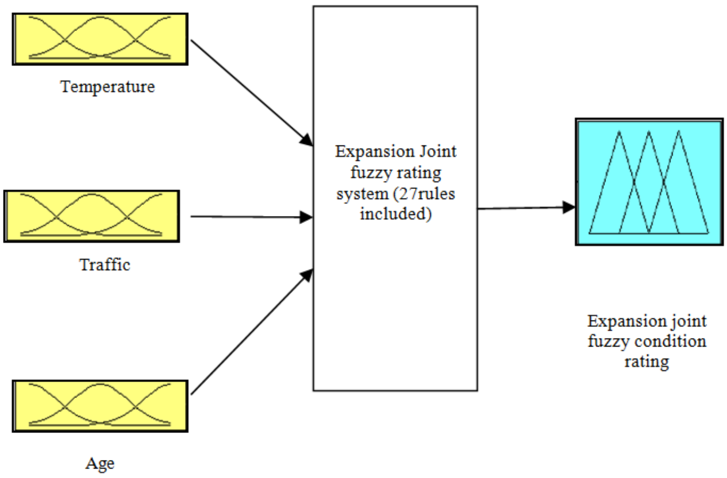


Figure 4-2 Fuzzy Inference System for joint condition elaboration

Matlab (2012) was used in developing the FL module. The membership functions were inserted and associated with the three contributing factors based on data extracted from the questionnaire survey which was introduced in chapter three.

4.3.1 MEMBERSHIP FUNCTIONS

(FL) requires the creation of membership functions that reflect qualitative perception of these factors with quantitative values. Accordingly, a membership function was established for each of the three contributing factors based on the procedure described below:

- ***Temperature:*** Temperature membership functions were created in accordance to Fisher (2005), where "*T*" is defined as the highest temperature throughout the entire summer months that was recorded for

1% of the duration. Moreover, temperature was described as either “Hot”, “Warm” or “Cold”, with the range of temperatures for each of these qualitative descriptions presented in Table 4.1 and Figure 4-3.

Table 4.1 Temperature Ranges (Fisher, 2005)

Temp.	***Range***
Cold	*-8 – 25*
Warm	*20 – 35*
Hot	*32 – 50*

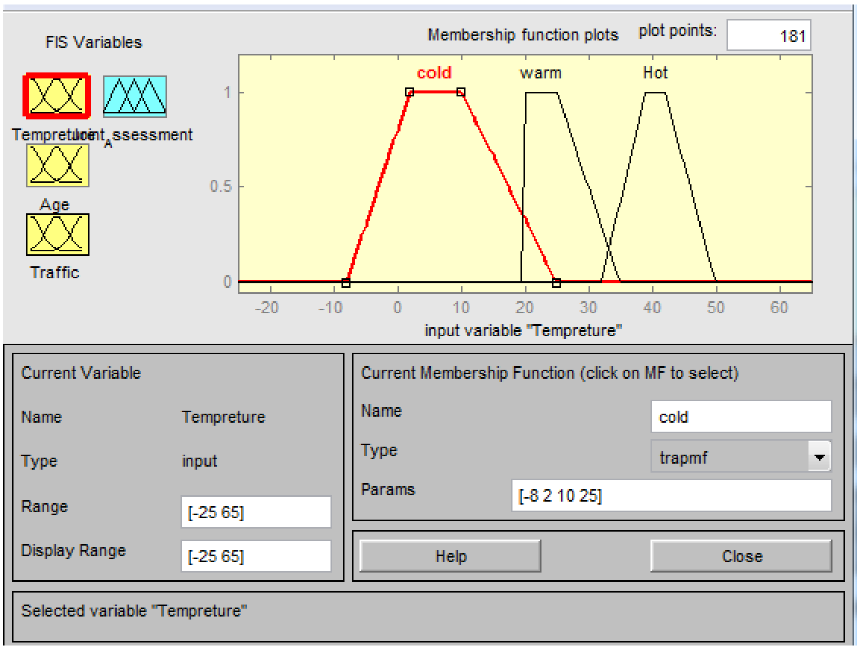


Figure 4-3 Membership function of temperature variable (Input)

- ***Expansion Joint Age:*** The expansion joint age membership function was described as either “New”, “Medium” or “Old”, Table 4.2 and Figure 4-4 present the quantitative ranges describing the age membership functions as extracted from the questionnaire (chapter 3).

Table 4.2 Age ranges of expansion joints

Age	**Range (years)**
New	0 - 4
Medium	2 - 8
Old	7 -16

Figure 4-4 Input Membership Function, Age Variable

- ***Average Daily Traffic Crossing the Bridge:*** (ADT) is an important factor that influences joint condition since higher ADT will result in faster deterioration rates to the expansion joint.

Table *4.3* and Figure 4-5 show the quantitative ranges that describe the membership function for ADT as being either “Low”, “Medium” or “High”. The ranges used in the membership function are based on the questionnaire analysis described in chapter 3. The critical condition exists when ADT and temperature are both at their maximum.

Table 4.3 Average Daily Traffic Ranges

ADT	***Range***
Low	*0 – 1000*
Medium	*800 – 3000*
High	*2500 - ∞*

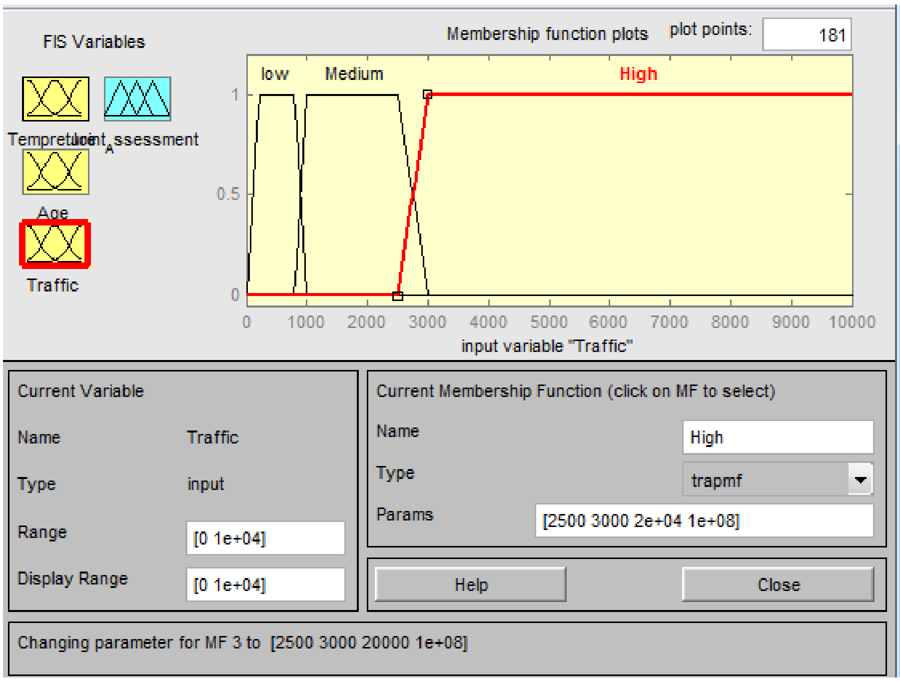


Figure 4-5 Membership Function of Average Daily Traffic Variable (Input)

Based on research conducted by (Khalid, 2003), it was shown that ADT increases during the summer months. Figure 4-6 shows the ADT flow distributed through the year with the peak happening in summer times (July & August). Moreover, it is shown that ADT is also highest during the afternoon. Table 4.4 and Figure 4-7 shows the distribution of ADT throughout the hours of a regular summer day, where temperatures are also expected to be highest.

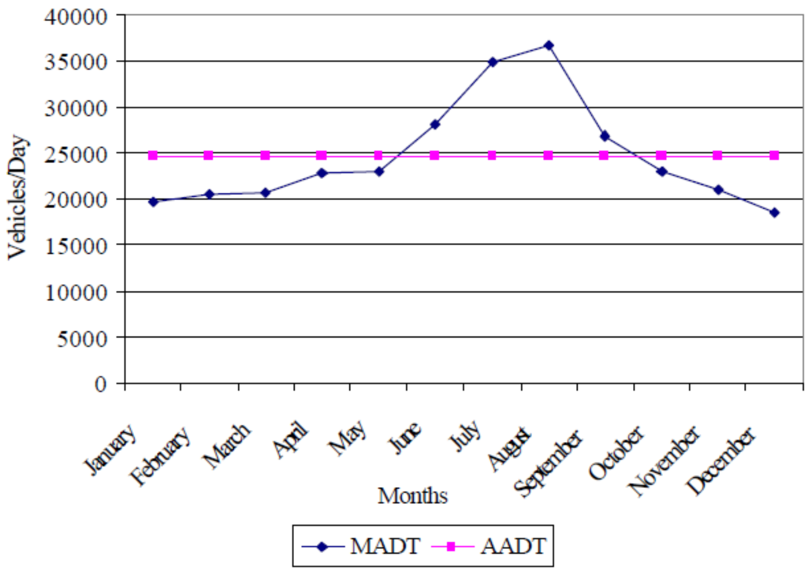


Figure 4-6 Comparison of Monthly Average Daily Traffic (MADT) in Egypt 2001 (Khalid A., 2003)

Table 4.4 Traffic Peak Periods in Greater Cairo Metropolitan Area (Cairo Traffic Congestion Study, 2012)

Peak	*Period*	*Percentage of occurrence in traffic count stations*
Morning	*07:00-09:00*	*29.1 %*
	10:00-12:00	*21.8 %*
Afternoon	*13:00-16:00*	*27.3 %*
	17:00-18:00	*9.1 %*
Evening	*20:00-21:00*	*12.7 %*
Total		*100 %*

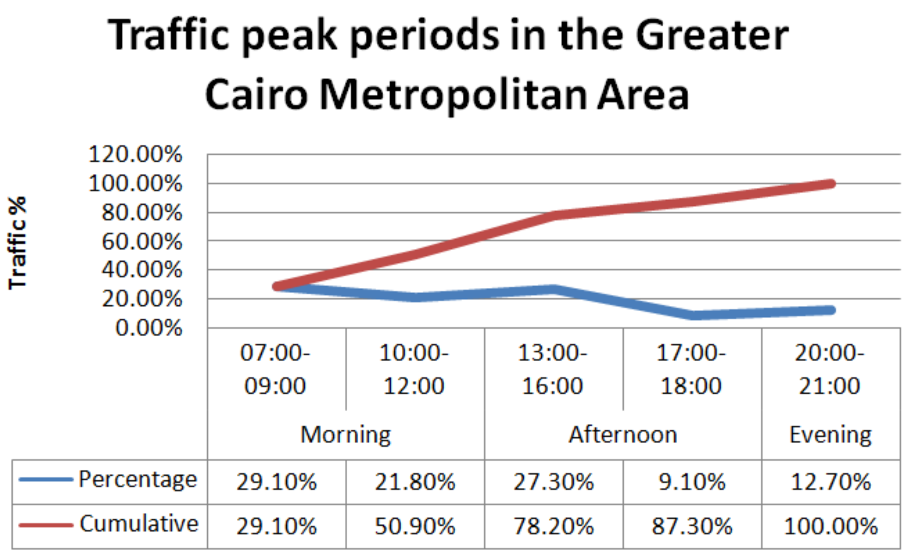


Figure 4-7 Traffic Peak Periods in Greater Cairo Metropolitan Area

4.3.2 ASSIGNING THE RELATIONSHIPS (IF-THEN RULES)

It is important to create the relationships among the various input factors such that output results can be extracted based on various input states. The input factors are provided into the model as a matrix, with the output presented based on the input. Data extracted from the questionnaires form the basis for creating the fuzzy rules that form the knowledge base of the model. Moreover, the model finally provides a prediction regarding the state of the joint based on a zero to 100 scale that describes the condition index (fuzzy logic output) of the joint as shown in Table 4.5.

Table 4.5 Description of condition state (output membership function)

Condition	*State*
<40	*Failure*
20-80	*Fair*
>60	*Good*

In order to create and simulate the relationships among the input and output conditions, Matlab Simulink (FL) controller was used (Matlab, 2012). The three contributing input factors (age, temperature and traffic) were correlated to the output conditions by employing “if, then” conditions. Twenty seven rules were defined based on information extracted from the questionnaire replies (Figure 4-8). Accordingly, based on these relationships and rules, if the age of the bridge, the temperature conditions and the traffic flow are known then the joint condition can be determined using the (FL) assessment model (Figure 4-9).

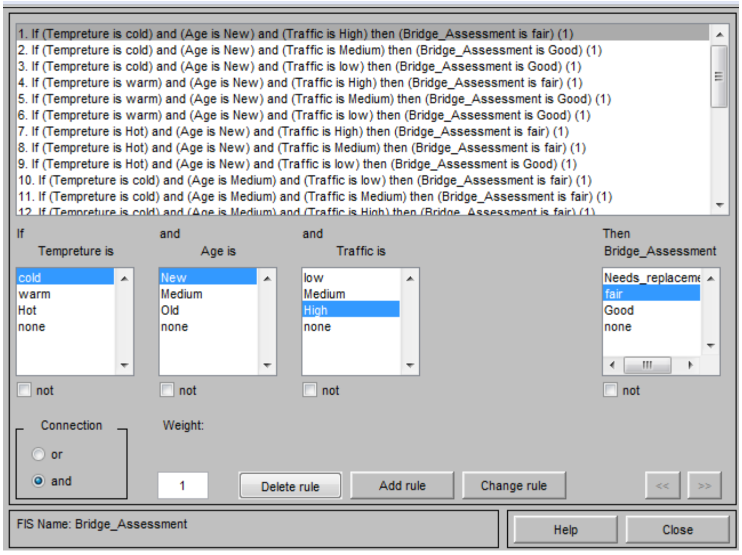


Figure 4-8 Assigning Rules between Membership Parameters

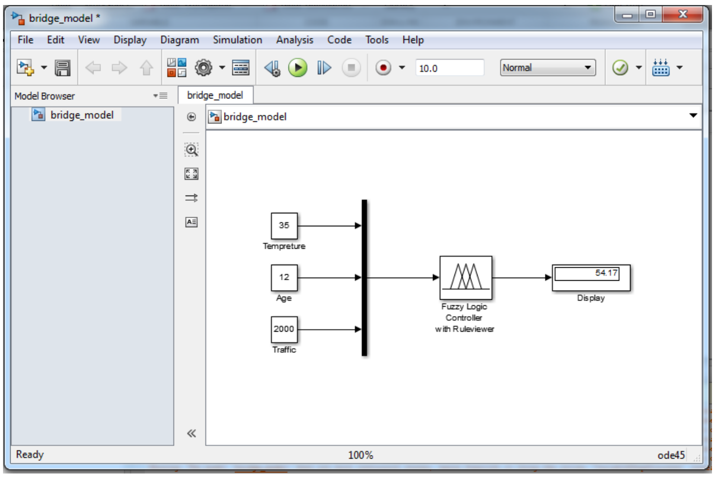


Figure 4-9 Fuzzy Logic Output View

4.3.3 TESTING OF FUZZY ASSESSMENT MODULE

The model was used to assess the conditions of thermal expansion joints in Egypt. The output of the model is the expected condition index based on a scale ranging from zero to 100 with 100 being the best condition and zero being the worst.

Table 4.6 below presents a case study that was used to test the module. The bridge being analyzed is Sixth of October Bridge, with the age at which the bridge is being analyzed in 5 years from the reference date of the model. Moreover, the bridge is expected to experience temperatures of 44 degrees Celsius, and an ADT of 30,000 vehicles per day. The module involves the functioning of the knowledge base which contains the information of these member functions as well as the rule base and involves converting the linguistic output variables into numerical variables or logical variables used to predict the EJ condition. Based on the input data, the (FL) assessment model characterized the overall joint conditions of the bridge as "fair" with percentage of 50% Table 4.6.

Table 4.6 Sixth of October bridge characteristics

Input	*Bridge*	*Sixth of October*
	Age	*After 5 years from last maintenance or rehabilitation*
	Temperature	*44 degrees Celsius*
	ADT	*30,000 Vehicles per day*
Output	*Overall Joins Condition*	*50% (Fair)*

Table 4.7 shows the condition rating of the expansion joints of sixth of October bridge based on the inspection carried out by bridge engineers. Applying the rating system scale 1-5 to the percentages of the condition rating, the overall

condition rating of the bridge joints is classified as fair. Equation (4.1) shows the calculation of the overall expansion joint.

Table 4.7 Sixth of October thermal joints condition in 2016

	Good	***Medium***	***Needs Replacement***	***Total***
Thermal Joint	*181 (63.5 %)*	*15(5%)*	*89 (31.5%)*	***285***

$$\begin{bmatrix}0 & 63.5 & 0 & 5 & 27\end{bmatrix}\times\begin{bmatrix}5 & 4 & 3 & 2 & 1\end{bmatrix} =$$

$$\frac{0*5+63.5*4+0*3+5*2+31.5*1}{100} = 2.95 \text{ (Fair)} \qquad (4.1)$$

By dividing the output condition over 5, the resulted number is the condition of 6 of October bridge joints on a zero to 100 scale = 59%

Applying the developed FL model for the EJ condition based on the data shown in Table (4-6), it was concluded that the output of the model that the overall EJ condition is FAIR (50%). By comparing the results retrieved from the assessment module and the results retrieved from visual inspection, it was noticed that the deviation between the two results are small (9%) and the module can predict the condition of thermal expansion joints with a low error margin.

4.4 EXPANSION JOINT DETERIORATION MODULE

It is also important to predict the deformation of expansion joints in order to forecast the performance of these joints. Accordingly, a (MC) Model was developed for predicting the condition of EJs based on current condition and the transition matrix of the expansion joints condition over years. Any EJ exists with the condition of being “Excellent”, “Good”, “Fair”, “Poor” or “Failing”. The transition matrix would describe the change percentages of each of these five states to another (Table 4.8).

Table 4.8 Transition Probability Matrix

		Preliminary Process					Sum
		To state					
		Excellent	Good	Fair	Poor	Failing	
From State	Excellent						100%
	Good	0					100%
	Fair	0	0				100%
	Poor	0	0	0			100%
	Failing	0	0	0	0	100	100%

The transition probability matrix presents the transition between each of state of joint conditions, where “State rating” describes the present condition of the joint compared to the initial condition after construction which is assumed to be 100%. It is important to note that the joint condition can be measured using a number of inspection methodologies, which could have a bearing on the results of inspection. Thus it is important that the methodology used for periodical inspections is unified in a project to enable comparison between inspection findings.

Hesham et al. (2016) developed a correlated between the condition of the joint and their rating on a zero to 5 scale. In addition, they suggested the feasible action that should be taken based on the current condition state (Table 4.9). The condition state proposed by Hesham et al. (2016) was adjusted in this research to match with the output range based on zero to 100 scale. Table 4.9 shows the correlation between the 0-5 scale and the proposed zero to 100 scale used in this research.

Table 4.9 State and feasible actions definitions (Hesham et al., 2016)

Condition	***Condition State***				
	0- 0.99	***1 – 1.99***	***2 – 2.99***	***3 – 3.99***	***4-5***
	0-19.9	***20 - 39.9***	***40 - 59.9***	***60 – 79.9***	***80-100***
	Failing	***Poor***	***Fair***	***Good***	***Excellent***
Condition Descriptions	*serious failures that affect safety so as serviceability*	*failures and defects that affect structural safety and serviceability*	*Minor defects,*	*No or minor defects*	*No defects at all*
Feasible actions	▪ *Rehabilitate* ▪ *Replace on the spot*	▪ *Repair* ▪ *Rehabilitate*	▪ *Protect* ▪ *Repair*	▪ *Protect*	▪ *Do Nothing*

4.4.1 EJ DETERIORATION MODEL: INPUT FACTORS

The output of the (FL) Assessment Model for each of the bridge's joints forms the input to the (MC) Model for predicting the future deterioration of EJs. Several steps need to be executed in order to determine the EJ condition at a desired year according to its current condition.

This study used the transition matrix which follows the structure shown in Equation (4.2). The initial transition matrix presented in Table 4.10 is based on the study conducted by (Orcesi et al., 2015), for Reinforced Concrete bridges in France during the period from 2009 to 2014.

$$\begin{array}{c} \\ \text{Excellent} \\ \text{Good} \\ \text{Fair} \\ \text{Poor} \\ \text{Failing} \end{array} \begin{array}{c} \begin{array}{ccccc} \text{Excellent} & \text{Good} & \text{Fair} & \text{Poor} & \text{Failing} \end{array} \\ \begin{bmatrix} P_{EE} & P_{EG} & P_{EF} & P_{EP} & 1-\sum P_{EX} \\ P_{GE} & P_{GG} & P_{GF} & P_{GP} & 1-\sum P_{GX} \\ P_{FE} & P_{FG} & P_{FF} & P_{FP} & 1-\sum P_{FX} \\ P_{PE} & P_{PG} & P_{PF} & P_{PP} & 1-\sum P_{PX} \\ P_{FaE} & P_{FaG} & P_{FaF} & P_{FaP} & 1-\sum P_{FaX} \end{bmatrix} \end{array} \qquad (4.2)$$

While this study initially used the transition matrix developed by (Orcesi et al., 2015) as the basis for the study, a transition matrix for Egypt's bridge thermal EJ was constructed in the optimization module of this study's framework, and will be described in Section 4.3 of this Chapter.

Table 4.10 Preliminary Process of Markov Chain "Transition Matrix" (Orcesi et al., 2015))

Preliminary Process					
	Excellent	Good	Fair	Poor	Failing
Excellent	83.7%	13.8%	2.1%	0.4%	0.0%
Good	0.0%	95.4%	3.8%	0.8%	0.0%
Fair	0.0%	0.0%	97.9%	2.1%	0.0%
Poor	0.0%	0.0%	0.0%	96.7%	3.3%
Failing	0.0%	0.0%	0.0%	0.0%	100.0%

By applying the deterioration process to bridge expansion joints assuming that it was constructed in 2016, the predicted joints condition will be as shown in Table 4.11. The table shows that the overall condition of the bridge EJ condition will go down from score 5.00 condition in 2016 to be in 3.80 in 2026.

Table 4.11 bridge expansion joint condition without applying maintenance plan

Year/Condition	Excellent	Good	Fair	Poor	Failing	ACI
2016	100.0%	0.0%	0.0%	0.0%	0.0%	5.00
2017	83.7%	13.8%	2.1%	0.4%	0.0%	4.81
2018	70.1%	24.7%	4.3%	0.9%	0.0%	4.64
2019	58.6%	33.2%	6.7%	1.4%	0.0%	4.49
2020	49.1%	39.8%	9.0%	2.0%	0.1%	4.36
2021	41.1%	44.8%	11.4%	2.6%	0.2%	4.24
2022	34.4%	48.4%	13.7%	3.3%	0.2%	4.13
2023	28.8%	50.9%	16.0%	4.0%	0.4%	4.04
2024	24.1%	52.5%	18.2%	4.7%	0.5%	3.95
2025	20.2%	53.4%	20.3%	5.5%	0.6%	3.87
2026	16.9%	53.7%	22.3%	6.2%	0.8%	3.80

Figure 4-10 presents the MC module interface, which includes the current condition of EJs produced from the FL assessment module and transition matrix for EJs. The current condition shown for example illustrates that 50% of the joints are in excellent condition while 10% are in Good condition, 15% are in Fair condition, 5% are in poor condition and finally 20% of the joints are in failing condition, this sums up for the 100% of the bridge joints. Applying MC deterioration matrix to the current condition in one year step would lead to the expected future condition shown in Figure 4-11.

This means that all the EJ that were excellent condition transferred to be in Good condition after 1 year of operation, and accordingly all the EJs will transfer one step down considering no maintenance will be carried out in this year.

Markov Based Deterioration Model

	Preliminary Process					Sum
	Excellent	Good	Fair	Poor	Failing	
Excellent	0.0%	100.0%	0.0%	0.0%	0.00%	100.00%
Good	0.0%	79.7%	20.3%	0.0%	0.00%	100.00%
Fair	0.0%	0.0%	69.8%	23.5%	6.72%	100.00%
Poor	0.0%	0.0%	0.0%	51.0%	49.02%	100.00%
Failing	0.0%	0.0%	0.0%	0.0%	100.00%	100.00%

Year/Condition	Excellent	Good	Fair	Poor	Failing	Sum
2016	50%	10%	15%	5%	20%	100%

(Current Condition) Input Data

Year/Condition	Excellent	Good	Fair	Poor	Failing	Check
2017	0.00%	57.97%	12.49%	6.08%	23.46%	100%

(2017 Condition) Output Data

Figure 4-10: Markov Chain module interface

Year/Condition	Excellent	Good	Fair	Poor	Failing
2017	0.00%	57.97%	12.49%	6.08%	23.46%
2018	0.00%	46.21%	20.48%	6.04%	27.28%
2019	0.00%	36.84%	23.66%	7.89%	31.61%
2020	0.00%	42.91%	23.45%	8.91%	24.72%
2021	0.00%	49.61%	22.77%	9.61%	18.00%
2022	0.00%	50.70%	23.28%	9.05%	16.96%
2023	0.00%	40.42%	26.53%	10.09%	22.96%
2024	0.00%	32.22%	26.71%	11.38%	29.69%
2025	0.00%	25.68%	25.17%	12.08%	37.06%
2026	0.00%	20.47%	22.77%	12.08%	44.68%

Figure 4-11: Expansion joint condition for 10 years

The model employed a consistent Markovian process that utilized a fixed transition matrix that spanned the period from 2009 to 2014.

In order to calculate the transition matrix at year *t+1,* Equation (4.3) can be used, which multiplies the transition matrix *P* of the previous years to calculate the matrix in the required year.

$$P_{t+1} = \prod_{i=1}^{t} P_i \tag{4.3}$$

Moreover, each bridge joints performance in a given year *t*, can be described based on Equation (4.4).

$$\lambda_t = \begin{bmatrix} T_1 & T_2 & T_3 & T_4 & T_5 \end{bmatrix} \tag{4.4}$$

Where, λ_t is the joint's performance matrix at year *t*, and *T* represents the joint's condition in percentage from 100=Excellent to 0= Failing.

Assuming a Markovian process, a transition matrix 2009-2014 is implemented. The model's next input is the bridge EJ current condition in 2016 in which the joint is being analyzed as presented in Table 4.12.

Table 4.12 Example of bridge Expansion Joint condition in 2016

Year/Condition	Excellent	Good	Fair	Poor	Failing
2016	50%	10%	15%	5%	20%

The EJ condition at year t+1 could be calculated by multiplying the EJ condition at year t and the EJ transition matrix. The outcome of EJ performance for the next 10 years will be as shown in Figure 4-11.

4.5 OPTIMIZATION MODULE

The overall framework of the model integrates the optimization module with the previously discussed deterioration module. The optimization module uses (GA) in order to construct the transition matrix for thermal EJs in Egypt and to determine the optimum maintenance plan for the joints, such that the condition of the joints is maximized while meeting an overall project budget.

4.5.1 TRANSITION MATRIX FOR THERMAL EXPANSION JOINTS IN EGYPT

In order to find out the transition matrix for expansion joints in Egypt, a case study was used. The transition matrix for thermal EJs in Egypt is determined using data retrieved from Kafr Dawood bridge which is located in Behira Governorate, Egypt.

The construction of Kafr Dawood Bridge was completed in June 1990. It consists of 10 EJs, with each joint measuring 11.5 m in length. While the bridge began operation in 1990, the first maintenance on the bridge was done in August 2001, with the second was done in July 2013. The goal of each maintenance activity was to raise the condition of the joints to an “Excellent” state.

In order to gain an understanding about the effectiveness of the conducted maintenance, visual inspection of the bridge was conducted in March 2017, with the results of this inspection shown in Table 4.13.

Table 4.13 Kafr Dawood inspection results of 2013 and 2017

Year/Condition	*Excellent*	*Good*	*Fair*	*Poor*	*Failing*
2013	*100%*	*0%*	*0%*	*0%*	*0%*
2017	*0%*	*40%*	*30%*	*20%*	*10%*

The transition matrix for the bridge's EJ in Egypt was constructed as shown in Table 4.14. This matrix is developed by determining the values of the coefficients that change the condition of the joints from its ideal state at the time of the last rehabilitation (2013) to the findings at the time in which the visual inspection took place (2017). GAs was used to minimize the error between the predicted state and the actual state in year 2017. Using the model, the target cells were the expansion joints condition in 2017 while the changeable cells were the transition matrix. The results of the model show the transition matrix for EJs in Egypt as shown in Table 4.14.

Objective Function: Minimizing the difference between the predicted condition and the inspected condition

Constrains: Sum of EJs conditions = 100%

Sum of transition matrix row = 100%

Variables: Transition Matrix cells

Table 4.14 Transition Matrix for Expansion Joints in Egypt

	Excellent	*Good*	*Fair*	*Poor*	*Failing*
Excellent	*0.0%*	*100.0%*	*0.0%*	*0.0%*	*0.0%*
Good	*0.0%*	*79.7%*	*20.3%*	*0.0%*	*0.0%*
Fair	*0.0%*	*0.0%*	*69.8%*	*23.5%*	*6.7%*
Poor	*0.0%*	*0.0%*	*0.0%*	*51.0%*	*49.0%*
Failing	*0.0%*	*0.0%*	*0.0%*	*0.0%*	*100.0%*

4.5.2 APPLYING ANNUAL MAINTENANCE PLAN

In order to apply annual maintenance plan for bridges EJs, The transition matrix was modified based on a proposed maintenance plan for the years that it follows. Figure 4-12 presents an example of a modified transition matrix for the years 2019, 2020 and 2021.

3-Year Transition Probability Matrix						
	Excellent	Good	Fair	Poor	Failing	Check
Excellent	0%	64%	30%	5%	1%	100%
Good	0%	51%	34%	10%	6%	100%
Fair	0%	87%	5%	3%	5%	100%
Poor	0%	66%	2%	4%	28%	100%
Failing	0%	37%	3%	0%	60%	100%

4-Year Transition Probability Matrix						
	Excellent	Good	Fair	Poor	Failing	Check
Excellent	0%	51%	34%	10%	6%	100%
Good	0%	40%	34%	13%	13%	100%
Fair	0%	74%	18%	2%	6%	100%
Poor	0%	80%	6%	1%	13%	100%
Failing	0%	59%	6%	0%	35%	100%

5-Year Transition Probability Matrix						
	Excellent	Good	Fair	Poor	Failing	Check
Excellent	0%	40%	34%	13%	13%	100%
Good	0%	32%	32%	15%	21%	100%
Fair	0%	67%	22%	4%	7%	100%
Poor	0%	87%	7%	1%	5%	100%
Failing	0%	92%	3%	0%	6%	100%

2019						
3-Year Transition Probability Matrix						
	Excellent	Good	Fair	Poor	Failing	Check
Excellent	0%	64%	30%	5%	1%	100%
Good	0%	51%	34%	10%	6%	100%
Fair	15%	74%	4%	3%	4%	100%
Poor	58%	28%	1%	2%	12%	100%
Failing	42%	21%	2%	0%	35%	100%

2020						
4-Year Transition Probability Matrix						
	Excellent	Good	Fair	Poor	Failing	Check
Excellent	0%	51%	34%	10%	6%	100%
Good	0%	40%	34%	13%	13%	100%
Fair	19%	60%	14%	2%	5%	100%
Poor	64%	29%	2%	0%	5%	100%
Failing	84%	9%	1%	0%	6%	100%

2021						
5-Year Transition Probability Matrix						
	Excellent	Good	Fair	Poor	Failing	Check
Excellent	0%	40%	34%	13%	13%	100%
Good	0%	32%	32%	15%	21%	100%
Fair	87%	9%	3%	1%	1%	100%
Poor	32%	59%	5%	0%	3%	100%
Failing	9%	83%	2%	0%	5%	100%

2019	
Condition	Maintenance Plan
Excellent	0%
Good	0%
Fair	15%
Poor	58%
Failing	42%

2020	
Condition	Maintenance Plan
Excellent	0%
Good	0%
Fair	19%
Poor	64%
Failing	84%

2021	
Condition	Maintenance Plan
Excellent	0%
Good	0%
Fair	87%
Poor	32%
Failing	9%

Excellent	Good	Fair	Poor	Failing	Check
13.55%	53.53%	19.61%	3.85%	9.46%	100%

Excellent	Good	Fair	Poor	Failing	Check
22.85%	41.66%	22.88%	6.39%	6.21%	100%

Excellent	Good	Fair	Poor	Failing	Check
16.45%	44.32%	21.36%	8.05%	9.82%	100%

Maintenance Cost	20.40	20.03	122.94
	163.36		

Maintenance Cost	23.80	33.25	80.78
	137.83		

Maintenance Cost	22.21	41.87	127.66
	191.75		

Figure 4-12 Markov Chain Annual Transition Matrix for 2019, 2020 and 2021

The model is then run based on a proposed Maintenance Plan (MP_t) for year t in accordance with the Matrix below (4.5):

$$MP_t = \begin{matrix} \text{Excellent} \\ \text{Good} \\ \text{Fair} \\ \text{Poor} \\ \text{Failing} \end{matrix} \begin{bmatrix} a\% \\ b\% \\ c\% \\ d\% \\ e\% \end{bmatrix} \tag{4.5}$$

Where *a* through *e* present the proposed maintenance percentage. For example if *e* was equal to 75%, this means that the maintenance plan proposes that 75% of failing joints be maintained and/or repaired for that year.

It should be noted that by modifying the maintenance plan, the transition matrix will also be modified. This adjusted transition matrix must reflect a condition of the model where any proposed maintenance plan would affect the joint condition from "fair, poor, or failure" condition to an “Excellent” condition.

Normally, the joint condition cannot change from a lesser to a better state without maintenance or rehabilitation being applied. The transition matrix is composed of an upper triangular matrix as shown in Table 4.15, where all elements below the main diagonal are zeroes to signify this assumption. Moreover, three of the cells below the main diagonal ("Fair, Poor and Failing" to Excellent) are modified to represent the maintenance plan for EJs.

Table 4.15: Transition Matrix Organization

Preliminary Process					
	Excellent	*Good*	*Fair*	*Poor*	*Failing*
Excellent		***The Main Diagonal***		***Transition percentages (Upper Triangular Matrix)***	
Good	*0.0%*				
Fair	***(optimized) Maintenance Plan***	*0.0%*			
Poor		*0.0%*	*0.0%*		
Failing		*0.0%*	*0.0%*	*0.0%*	

Moreover, once a maintenance plan is chosen, the new transition matrix is modified to account for the fact that maintenance can lead to the state of a joint improvement. This new transition matrix P_{ipx} is calculated using Equation (4.6)

$$P_{ipx} = \begin{array}{c} \text{Excellent} \\ \text{Good} \\ \text{Fair} \\ \text{Poor} \\ \text{Failing} \end{array} \begin{bmatrix} a & 1-a\times\dfrac{P_{EG}}{\sum P_{EX}} & \cdots & \cdots & 1-a\times\dfrac{P_{EFa}}{\sum P_{EX}} \\ b & \vdots & \ddots & & \vdots \\ c & \vdots & & \ddots & \vdots \\ d & \vdots & & & \vdots \\ e & 1-a\times\dfrac{P_{FaG}}{\sum P_{FaX}} & \cdots & \cdots & 1-a\times\dfrac{P_{FaFa}}{\sum P_{FaX}} \end{bmatrix} \qquad (4.6)$$

Accordingly, the joint condition at year *t+1*, taking into account the proposed maintenance plan is calculated based on Equation (4.7).

$$\lambda_{(t+1)} = \prod_{i=1}^{t} P_{(i+1)pbx} \times Q_t \qquad (4.7)$$

Where Q_t is the condition of bridge EJs in year i

Based on the given expansion joint condition and the transition matrix, the model calculates the (ACI) as a measure of the joints performance. This index ranges from 0 to 5 with zero representing a failing condition and 5 representing an excellent condition. Accordingly, the joints performance matrix λ_i is translated into ACI according to Equation (4.8).

$$ACI = \lambda_i \times \begin{bmatrix} 5 & 4 & 3 & 2 & 1 \end{bmatrix} \quad (4.8)$$

Where $\lambda_i = \begin{bmatrix} T_1 & T_2 & T_3 & T_4 & T_5 \end{bmatrix}$

As an example, if the performance matrix, at the 7th year is, $\lambda_7 = \begin{bmatrix} 0 & 40.42 & 26.53 & 10.09 & 22.96 \end{bmatrix}$, then ACI in 2024 can be calculated as follows:

$$\text{ACI} = 5*\text{T}_1 + 4*\text{T}_2 + 3*\text{T}_3 + 2\text{T}_4 + \text{T}_5$$

$$ACI = \begin{bmatrix} 0 & 40.42 & 26.53 & 10.09 & 22.96 \end{bmatrix} \times \begin{bmatrix} 5 & 4 & 3 & 2 & 1 \end{bmatrix} =$$

$$\frac{0*5 + 40.42*4 + 26.53*3 + 10.09*2 + 22.96*1}{100} = 2.84 \text{ (Fair)}$$

4.5.3 LIFE CYCLE COST CALCULATION

In order to assess the life-cycle cost, the initial cost is accounted for through the joint’s cost. This cost is determined based on the market price of the thermal joints as shown in Table 4.16 which reflects the market price of the joints in year 2016.

Based on the proposed maintenance plan the lifecycle cost can then be computed. Moreover, the proposed maintenance plan is amended until life-cycle cost is optimized along with the joint’s (ACI).

Table 4.16 Input of joint initial cost in 2016

Item/Cost	*Cost/ m (L.E)*
Thermal Joint	*5,200.00*

According to VDOT (2014), the maintenance cost accounts for 2% of the initial cost in the event that the joint condition is raised from fair to excellent, however, the maintenance cost of EJs is expected to reach 10% in the case that the joint condition is required to be raised from poor to excellent condition. A maintenance cost of 25% in the case of raising the joint condition failing to excellent condition (Table 4.17).

Table 4.17 Maintenance cost calculation

Maintenance Cost	
Condition	*Annual Maintenance Cost (L.E)*
Excellent	*0*
Good	*0*
Fair	*104.00 (2%*Initial Cost)*
Poor	*520.00 (10%* Initial Cost)*
Failing	*1300.00 (25%* Initial Cost)*

Moreover, based on this and the previously calculated Maintenance Plan (Equation (4.9) extracted from the (MC) model, the Maintenance Cost (C_t) for year *t* can be calculated as follows:

$$C_t = MP_t \times IC * [0 \quad 0 \quad 2\% \quad 10\% \quad 25\%] * \text{The length of EJs} \qquad (4.9)$$

Where:

IC is the EJ initial cost per meter length

MP_t is the maintenance plan at year t

An example of calculating the maintenance cost is shown in Table 4.18. Assuming the percentage of fair EJs is 13.5%, the total length of EJs in the bridge is 400 m, the maintenance cost is calculated as shown in equation (4.9) and Table 4.18

Table 4.18 Expansion Joints Maintenance Cost

Maintenance Cost			
	Fair	Poor	Failing
Maintenance plan (%)	13.5%	10.5%	25.7%
Maintenance Cost (L.E)	14.04	54.6	334.1
Total Cost (L.E)/ m.l			402.74
Total Cost for the bridge (L.E)			161096

Moreover, if the Maintenance Cost (C_t) is calculated at every year throughout the bridge's life span, the Life-Cycle Cost (LCC) can be calculated based on Equation (4.10).

$$LCC = IC + \sum_{t=1}^{n} C_t \qquad (4.10)$$

Nonetheless, when calculating Life-Cycle Cost it is essential to account for the varying time value of money throughout the bridge's lifespan. Accordingly, inflation rate is taken into account to calculate the total life cycle cost (TLCC) through Equation (4.11).

$$TLCC = IC + \sum_{t=1}^{n} \left(C_t \times \prod_{t=1}^{n} (1 + IR_t) \right) \qquad (4.11)$$

Where IR_t is the inflation rate at year t. In this study an annual inflation rate of 24.3% for Egypt according to CAPMAS (2016) was used (Figure 4-13).

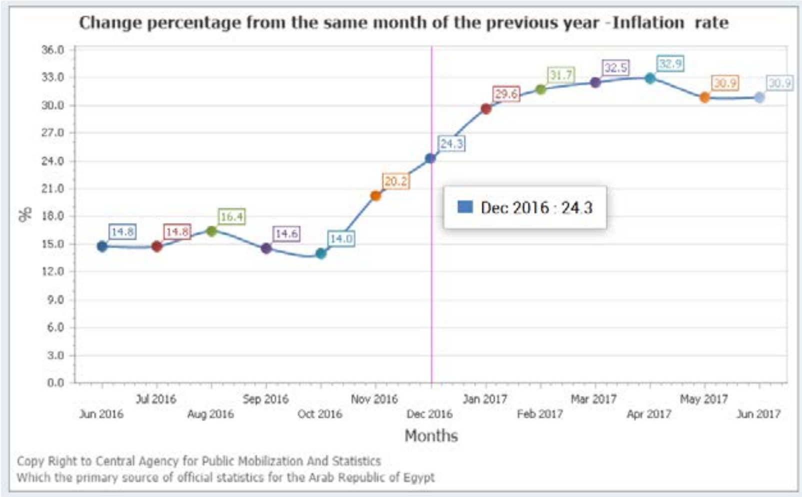


Figure 4-13: Change in Egyptian currency Inflation rate (CAPMAS)

Furthermore, the model provides the percentage of conditions for the EJs and calculates the (ACI) for each year in the 10 year time frame (Table 4.19). The table shows the change in annual condition index every year. The annual condition index varies depending on the condition transition matrix and the maintenance plan applied.

Table 4.19 percentages of all expansion joint conditions in 10 years

Year/Condition	Excellent	Good	Fair	Poor	Failing	ACI
2016	50.00%	10.00%	15.00%	5.00%	20.00%	3.65
2017	0.00%	57.97%	12.49%	6.08%	23.46%	3.05
2018	0.00%	46.21%	20.48%	6.04%	27.28%	2.86
2019	0.00%	36.84%	23.66%	7.89%	31.61%	2.66
2020	0.00%	42.91%	23.45%	8.91%	24.72%	2.85
2021	0.00%	49.61%	22.77%	9.61%	18.00%	3.04
2022	0.00%	50.70%	23.28%	9.05%	16.96%	3.08
2023	0.00%	40.42%	26.53%	10.09%	22.96%	2.84
2026	0.00%	20.47%	22.77%	12.08%	44.68%	2.19
Average ACI						2.84

The user is also capable of printing tables and graphs that represent annual and cumulative costs as shown in Table 4.20, Table 4.21, Figure 4-14 and Figure 4-15. Furthermore, the model calculates the (ACI) as shown in (Table 4.22 and Figure 4-16).

Table 4.20 Life cycle cost

Annual Inflation Rate (%)	24.3%											
Inflation Rate (%)	1.00	1.24	1.49	1.73	1.97	2.22	2.46	2.70	2.94	3.19	3.43	
Life Cycle Cost												
Total Cost/Year	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	Total Life Cycle Cost
Total Cost (L.E)	5,200	56.99	55.43	54.39	53.76	53.42	53.31	53.36	53.76	54.37	54.04	5,742.82
Total Cost (L.E)	5,200	70.84	82.36	94.04	106.01	118.33	131.03	144.11	158.25	173.26	185.37	6,463.62

Table 4.21 Expansion joint annual and cumulative cost

Year	***Cost***	
	Annual	*Cumulative Table*
2016	*5,200.00*	*5,200.00*
2017	*70.84*	*5,270.84*
2018	*82.36*	*5,353.20*
2019	*94.04*	*5,447.24*
2020	*106.01*	*5,553.25*
2021	*118.33*	*5,671.58*
2022	*131.03*	*5,802.62*
2023	*144.11*	*5,946.73*
2024	*158.25*	*6,104.98*
2025	*173.26*	*6,278.25*
2026	*185.37*	*6,463.62*

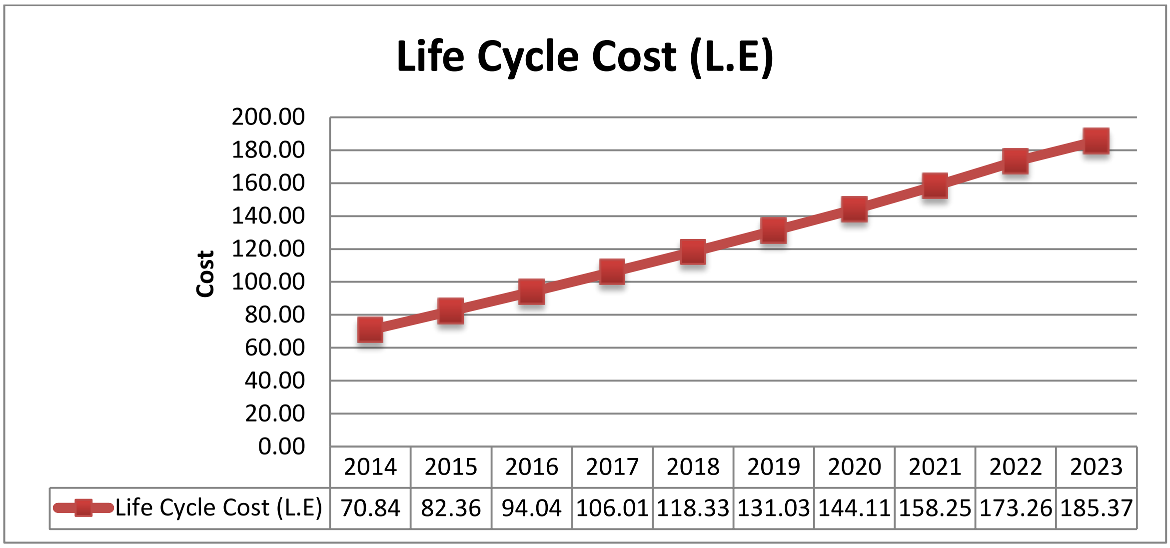


Figure 4-14 Annual Cost for Expansion Joints Maintenance

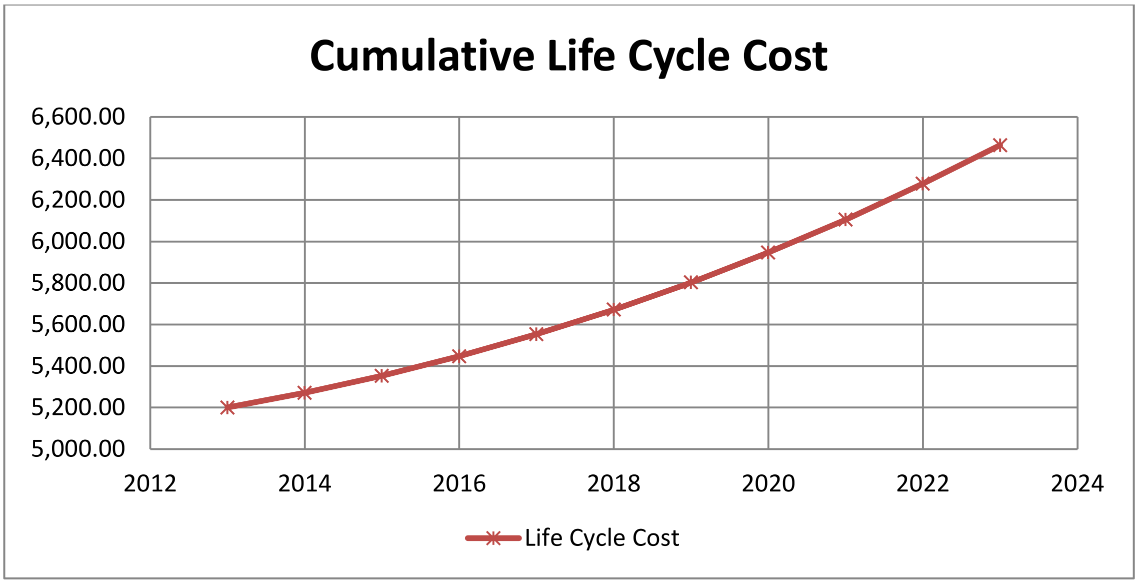


Figure 4-15 Cumulative Cost for Expansion Joint Maintenance

Table 4.22 Annual condition index for Expansion Joints

Annual ACI Table	
Year	*Annual ACI*
2016	*4.45*
2017	*4.24*
2018	*4.17*
2019	*4.10*
2020	*4.05*
2021	*4.01*
2022	*3.97*
2023	*3.94*
2024	*3.89*
2025	*3.86*
2026	*3.87*

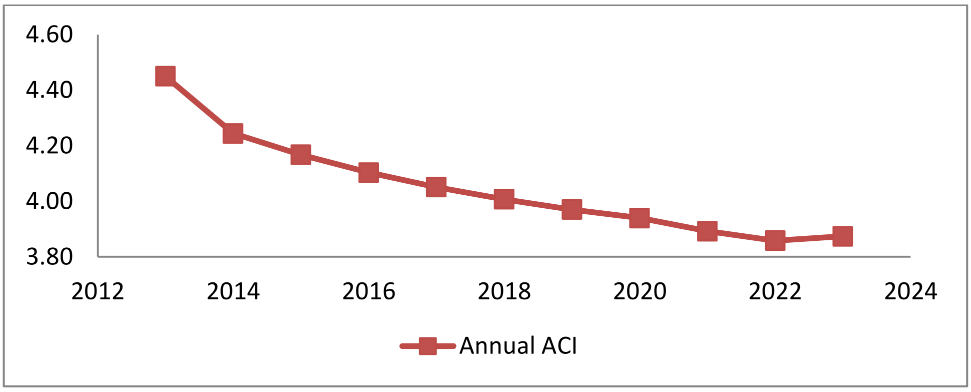


Figure 4-16 Annual Condition Index

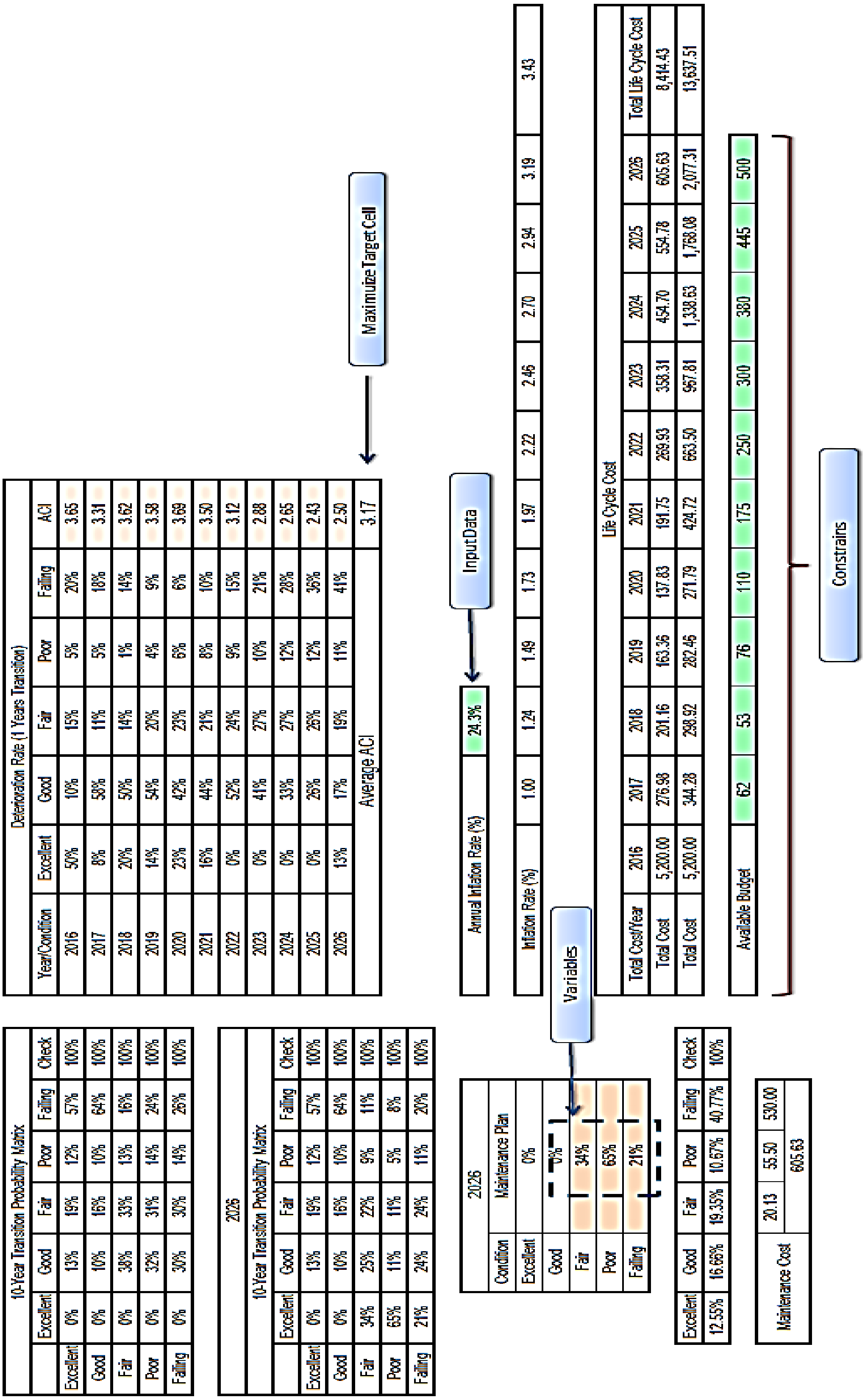
4.5.4 OPTIMUM MAINTENANCE PLAN

Optimum maintenance plan would vary according to the given constrains. The optimum maintenance plan of a given limited budget is different from the optimum maintenance plan targeting the maximum annual condition index. The objective functions in all coming modules are maximizing the annual condition index while changing the module constrains only. Each constrain will be discussed separately.

TARGETING A GIVEN BUDGET

Optimal maintenance plan can be determined given an available budget (Figure 4-17). This reflects real life conditions where the decision makers most of the time have limited budget and they want to achieve the optimum ACI within this limited budget.

This optimization module is developed in order to decide on the percentages of repair and maintenance that should be done for bridges EJs in each state. For example Figure 4-17 show that the condition state at year 2017 is [8 58 11 5 18] with 3.31 ACI and the proposed maintenance plan is to maintain 57% of fair condition to be in excellent condition and 54% of poor condition to be in excellent condition and 90% of failure condition to be in excellent condition.



10-Year Transition Probability Matrix						
	Excellent	Good	Fair	Poor	Failing	Check
Excellent	0%	13%	19%	12%	57%	100%
Good	0%	10%	16%	10%	64%	100%
Fair	0%	38%	33%	13%	16%	100%
Poor	0%	32%	31%	14%	24%	100%
Failing	0%	30%	30%	14%	26%	100%

2026 10-Year Transition Probability Matrix						
	Excellent	Good	Fair	Poor	Failing	Check
Excellent	0%	13%	19%	12%	57%	100%
Good	0%	10%	16%	10%	64%	100%
Fair	34%	25%	22%	9%	11%	100%
Poor	65%	11%	11%	5%	8%	100%
Failing	21%	24%	24%	11%	20%	100%

Deterioration Rate (1 Years Transition)						
Year/Condition	Excellent	Good	Fair	Poor	Failing	ACI
2016	50%	10%	15%	5%	20%	3.65
2017	8%	58%	11%	5%	18%	3.31
2018	20%	50%	14%	1%	14%	3.62
2019	14%	54%	20%	4%	9%	3.58
2020	23%	42%	23%	6%	6%	3.69
2021	16%	44%	21%	8%	10%	3.50
2022	0%	52%	24%	9%	15%	3.12
2023	0%	41%	27%	10%	21%	2.88
2024	0%	33%	27%	12%	28%	2.65
2025	0%	26%	26%	12%	36%	2.43
2026	13%	17%	19%	11%	41%	2.50
Average ACI						3.17

2026	
Condition	Maintenance Plan
Excellent	0%
Good	0%
Fair	34%
Poor	65%
Failing	21%

Excellent	Good	Fair	Poor	Failing	Check
12.55%	16.66%	19.35%	10.67%	40.77%	100%

Maintenance Cost	20.13	55.50	530.00
	605.63		

Annual Inflation Rate (%)	24.3%

Inflation Rate (%)	1.00	1.24	1.49	1.73	1.97	2.22	2.46	2.70	2.94	3.19	3.43

Life Cycle Cost												
Total Cost/Year	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	Total Life Cycle Cost
Total Cost	5,200.00	276.98	201.16	163.36	137.83	191.75	269.93	358.31	454.70	554.78	605.63	8,414.43
Total Cost	5,200.00	344.28	298.92	282.46	271.79	424.72	663.50	967.81	1,338.63	1,768.08	2,077.31	13,637.51

Available Budget	62	53	76	110	175	250	300	380	445	500

Figure 4-17 Targeting maximum condition at a certain budget

The model provides recommendation regarding the optimum maintenance plan based on an inputted annual maintenance budget. The input data provided to the model is shown in Table 4.23.

Table 4.23 Annual Available Maintenance Budget

Year	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026
Available Budget	62	53	76	110	175	250	300	380	445	500

The objective function is to maximize the annual condition index within a given annual available budget.

Objective Function: Maximizing ACI

Constrains: The Available budget

Sum of transition matrix row = 100%

Variables: Maintenance plan cells

Based on the provided inputs, the model outputs annual maintenance plans as shown in Table 4.24

Table 4.24 Annual Maintenance Plan

	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026
Excellent	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Good	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Fair	57%	73%	100%	100%	3%	100%	100%	100%	9%	34%
Poor	54%	100%	58%	58%	25%	98%	98%	100%	0%	65%
Failing	90%	1%	23%	23%	0%	9%	9%	100%	90%	21%

MINIMIZING THE AVERAGE FAILING CONDITION

Bridge Management systems requires developing deterioration models that are capable of predicting the declination of the bridge, this would be a great benefit for decision makers in structuring the most appropriate maintenance plan for their projects (Sobanjo, 1997).

In this research, the (MC) model is combined with (GA) in order to determine the optimum maintenance plan, by optimizing between two variables; average failing state and life-cycle cost. Accordingly, the model selects the optimum maintenance plan that minimizes the failing state and the LCC.

Table 4.25 presents a simulation of the model, where the model targets a 45% average failing state percentage for the simulated years, and thus selects a maintenance plan that meets this target while minimizing total life cycle cost TLCC.

Table 4.25 Average Failing Condition with TLCC targeting 45% failing percent

Deterioration Rate (1 Years Transition)						
Year/Condition	Excellent	Good	Fair	Poor	Failing	ACI
2016	50%	10%	15%	5%	20%	3.65
2017	0%	58%	12%	6%	23%	3.05
2018	0%	46%	20%	6%	27%	2.86
2019	0%	37%	24%	8%	32%	2.66
2020	0%	29%	24%	10%	37%	2.46
2021	0%	23%	23%	11%	43%	2.26
2022	0%	19%	21%	11%	50%	2.08
2023	0%	15%	18%	10%	57%	1.91
2024	0%	12%	16%	10%	63%	1.76
2025	0%	9%	13%	9%	69%	1.64
2026	0%	8%	11%	7%	74%	1.53
Average Failing Condition					45%	
Total Life Cycle Cost (TLCC)					12,014.01	

This step is repeated for different percentages of average failing states with the TLCC calculated for each. Finally the TLCC is plotted against average failing percentage (Figure 4-18), in order to determine the optimal maintenance plan.

(Min. TLCC , Minimum Failing Condition) Sensetivity Anallysis

% of failing	14%	15%	20%	25%	30%	35%	40%	45%
TLCC	7440	7,579.44	8,298.19	9,020.46	9,730.38	10,514.50	11,270.45	12,014.01

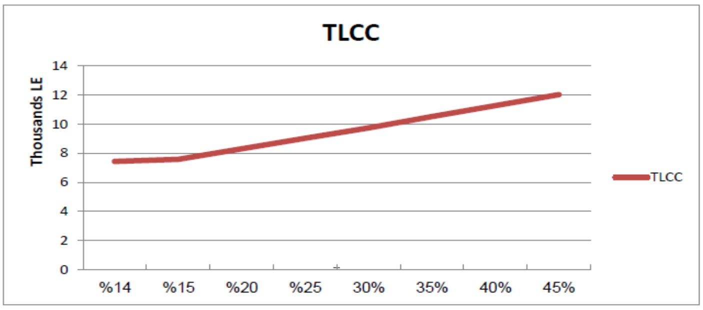


Figure 4-18 Average Failing Condition Sensitivity Analysis

4.5.5 TARGETING AVERAGE ACI WITH MINIMUM TLCC

As previously stated, the model combines the (MC) model with (GA) in order to provide decision makers with the appropriate maintenance plan that leads to the least TLCC for an average (CI). Table 4.26 presents the lifespan cost for a 3.5 average (ACI).

Table 4.26 Average Failing Condition with TLCC

Deterioration Rate (1 Years Transition)						
Year/Condition	Excellent	Good	Fair	Poor	Failing	ACI
2016	50%	10%	15%	5%	20%	3.65
2017	35%	58%	2%	3%	2%	4.20
2018	19%	66%	13%	1%	1%	4.03
2019	6%	67%	22%	3%	1%	3.73
2020	8%	53%	28%	7%	4%	3.53
2021	31%	30%	22%	8%	9%	3.67
2022	3%	53%	21%	9%	14%	3.21
2023	6%	41%	24%	9%	20%	3.03
2024	39%	12%	15%	9%	25%	3.33
2025	32%	17%	13%	8%	30%	3.14
2026	27%	20%	11%	7%	35%	2.97
Average ACI						**3.50**
Total Life Cycle Cost (TLCC)						**7669**

This step is repeated for different values of ACI with the TLCC calculated for each. Finally, the TLCC is plotted against average ACI (Figure 4-19) in order to determine the optimal maintenance plan. It can be noticed from the figure that the failing percentage and TLCC increase with ACI decreasing which means that maintaining the expansion joints periodically leads to minimizing the TLCC and the failing percentage.

Min. TLCC , Target Average ACI

ACI	2.5	3	3.5	3.7
TLCC	11397	9526	7669	7433
Failing %	40%	26%	15%	14%

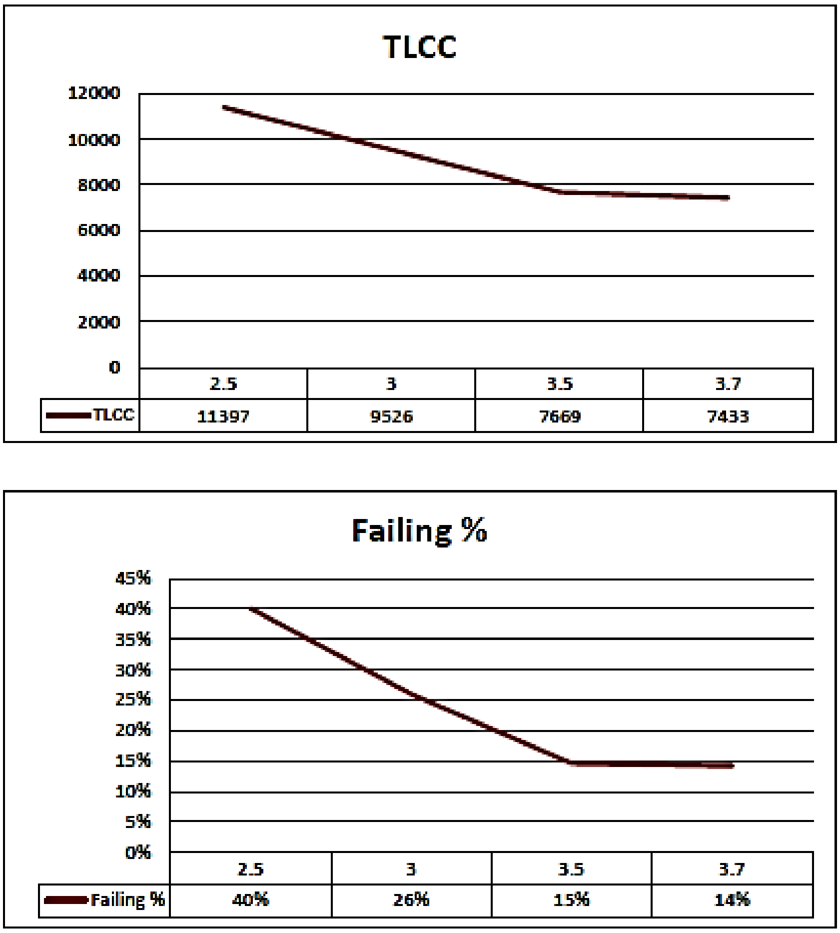


Figure 4-19 Average ACI with Minimum TLCC

4.5.6 MODEL VALIDATION

It is vitally important to validate the results of the model in order to ensure that the output results reflect what actually takes place. Accordingly, Elbadrasheen and Bashteel bridges are used to validate the model.

FIRST CASE STUDY (ELBADRASHEN BRIDGE)

Elbadrasheen bridge which is located in Giza governorate was used to validate the model results, through comparing the model's output results with real life conditions.

The construction of Elbadshasheen bridge was completed in September 2014, with a visual inspection of the bridge conducted in January 2017. Moreover, the bridge is composed of two bridges as shown in the bridge layout in Figure 4-20, with each of the bridges carrying traffic in opposite directions. The primary purpose of this bridge is to crossover Elgizaweya Canal and railway. The deck width of each bridge is seven meters, with the length of each spanning 450 m. The first bridge is composed of 11 spans and 2 ramps, while the second is composed of 8 spans and 2 ramps. Interestingly, each of the bridges has a different statistical system; with the first being a steel system and the second being a precast reinforced concrete system. This provides a variation in bridge and joint types that can aid in the verification process.

Moreover, thermal joints were used as between the precast concrete sections of the bridge, while strip seal joints were used in the steel spans.

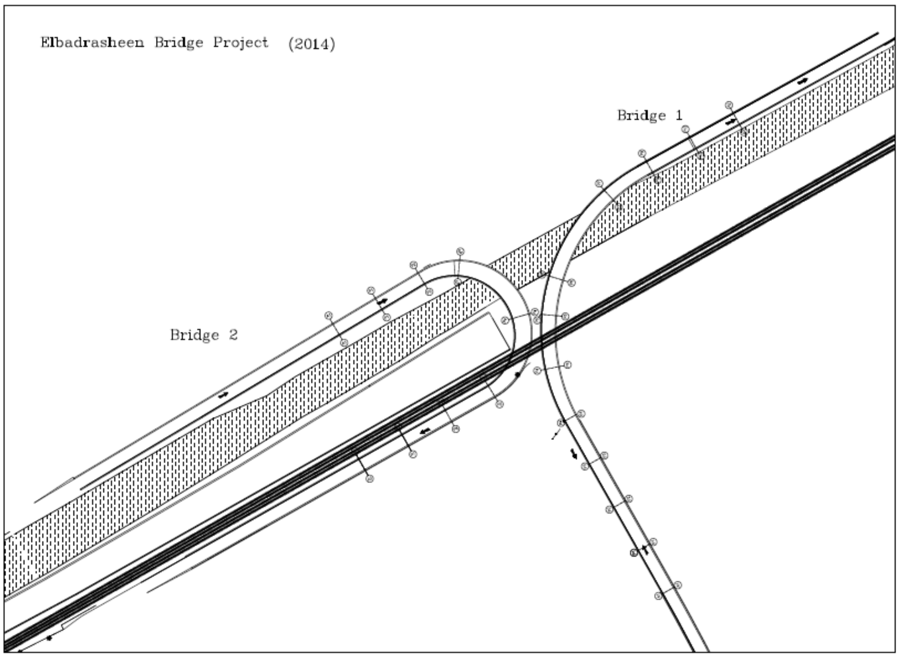


Figure 4-20 Elbadrasheen Bridge Layout

In order to assess the existing condition of the bridge EJs, the (FL) model was used. Based on collected data regarding the bridge, it was noted that the age of the bridge was 3 years; the temperature at which the bridge exists is 44 degrees Celsius, with an ADT of 900 vehicles per day Table 4.28. The results of this model were compared against the findings from the conducted visual inspection in order to validate the model's output.

Table 4-27 Elbadrasheen bridge characteristics

Input	*Bridge*	*Elbadrasheen Bridge*
	Age	*After 3 years from last maintenance or rehabilitation*
	Temperature	*44 degrees Celsius*
	ADT	*900 Vehicles per day*
Output	*Joint Condition*	*2.42 (48%)*

Based on the input, the model's output presented an average ACI of 2.42. Moreover, as shown Table 4.28, the conducted visual inspection presented an average ACI of 2.57. This illustrates the accuracy of the model where the model results deviated from the actual conditions by 6%.

Table 4.28 Condition of Elbadrasheen Bridge Expansion Joints

	Joint No.												Average ACI
Joint No. (Bridge 1)	1	2	3	4	5	6	7	8	9	10	11	12	2.57
Condition Rate	2.50	1.90	2.30	3.20	2.40	S.S	S.S	S.S	2.00	3.10	3.10	2.50	
Joint No. (Bridge 2)	1	2	3	4	5	6	7	8	9	10			
Condition Rate	2.10	1.90	3.20	3.00	S.S	S.S	S.S	2.90	3.10	1.90			

S.S: Strip Seal Joint

SECOND CASE STUDY (BASHTEEL BRIDGE)

Bashteel bridge located in Cairo, has a deck width of 13.5 m, with a total length of 520 m (Figure 4-21). The bridge's construction was completed in December 2014, with visual inspection of the bridge conducted in March 2017. The main purpose of the bridge is to overcome a railway crossing, and is composed of 11 spans with 2 ramps serving the bridge. Just as with Elbadrasheen bridge, Bashteel bridge is composed of two different type of spans, steel and precast reinforced concrete. Furthermore, asphalt plug joints were used as thermal joints between the precast concrete sections of the bridge, while strip seal joints were used in the section of the bridge composed of steel.

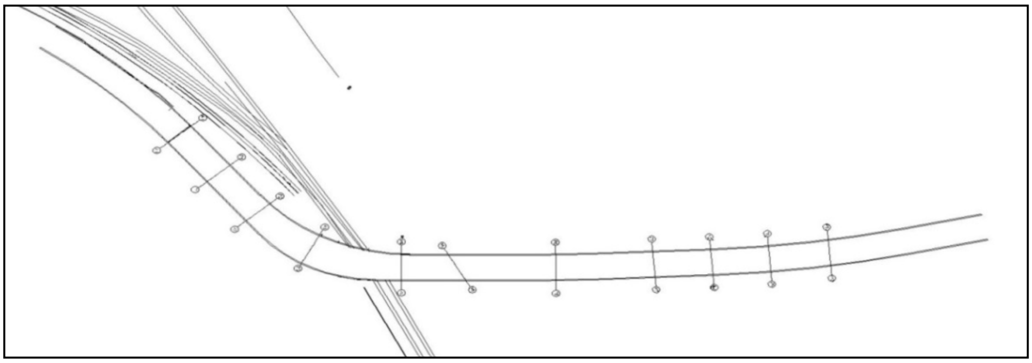


Figure 4-21 Bashteel Bridge Layout

Based on the collected data regarding Bashteel bridge, it was found that the bridge age is 2.2 years, operating at a temperature of 44 degrees Celsius and carrying an ADT of 1200 vehicles per day. This input data regarding the bridge was inputted into the (FL) assessment model where the model showed that the average ACI is (2.3) Table 4-29. Based on the visual inspection of the bridge's joint condition it was determined that the average ACI is 2.21 (Table 4.30), which illustrates a deviation of approximately 4%. This relatively small percentage highlights the accuracy of the model's results.

Table 4-29 Bashteel bridge characteristics

Input	*Bridge*	*Elbadrasheen Bridge*
	Age	*After 2.2 years from last maintenance or rehabilitation*
	Temperature	*44 degrees Celsius*
	ADT	*1200 Vehicles per day*
Output	*Joint Condition*	*2.3 (46%)*

Table 4.30 Bashteel Bridge expansion joints condition

	Joint No.											Average ACI
Joint No.	1	2	3	4	5	6	7	8	9	10	11	2.21
Condition Rate	2.20	2.00	2.80	1.90	S.S	S.S	1.95	2.10	2.30	2.30	2.30	

S.S: Strip Seal Joint

VALIDATION SUMMARY

Table 4.31 presents a summary of the model's output for Elbadrasheen and Bashteel bridges versus those obtained from actual visual inspections. As noted the model presents a percentage different of less than 10 percent versus results obtained from visual inspections for each of the cases analyzed. This validates the consistent nature of the model's accuracy.

Table 4.31 Summary of model's output during validation and verification process

Bridge	*Average ACI from Model*	*Average ACI from visual inspection*	*Percentage difference*
Elbadrasheen	*2.42*	*2.57*	*5.8*
Bashteel	*2.3*	*2.21*	*3.9*

4.6 SUMMARY

Chapter Four presented the model's framework in greater depth, highlighting the main modules of the model is composed of 3 modules: the condition assessment module through the use of (FL); the deterioration module through the use of (MC), and the optimization module through the use of (GA).

Furthermore, the benefits of the model were highlighted, with great emphasis on how the EJMS can be beneficial for highway agencies and authorities to aid in their decision making process.

Moreover, in order to validate the model's results, Elbadrasheen bridge was used, where the model's output was compared to visual inspections of the bridge. It was noted that the model produced results that deviated from real life condition by only 5.8%. Furthermore, these results were also validated by applying the model to another bridge, Bashteel bridge, where the model produced results that deviated from the bridge's real life conditions by only 3.9%. These results highlight the accuracy of the model as well as its potential applicability to bridges in Egypt on a nationwide scale.

CHAPTER 5
CONCLUSION AND RECOMMENDATIONS

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 CONCLUSION

Bridges form an important element of any nation's critical infrastructure. They can help connect a road network thus helping improve trade and business potential, which can help drive an economy. Nonetheless, such networks require periodic maintenance and repair to ensure that they are able to fulfill their purpose in the short-term, while minimizing potential replacement of bridge elements in the long-term and extending the bridge elements' life-span.

EJs are one of the bridge's most important elements. These joints are exposed to environmental conditions including temperature and pollution as well as physical loads including vehicle traffic and contraction and expansion of the bridge. By prolonging these elements' life-span the bridge overall Life-Cycle Cost is reduced.

This study presents an Expansion Joint Management System (EJMS) that is capable of reaching a maintenance plan that reduces the Total Life-Cycle Cost. This offers an important tool for decision makers in ensuring that decisions are based not only on initial cost but that maintenance cost is also accounted for.

The proposed model is composed of a number of modules that are connected together within an integrated framework. The first of these modules is the assessment module which uses (FL) in order to assess the joint's condition. The established fuzzy rules were composed from a survey of 75 experts. The assessment is then conducted through inputting into the model information regarding a bridge's; age, surrounding temperature and (ADT). This overcomes that lack of available information regarding the joint's maintenance history, and thus is capable of forecasting the state of the joint in spite of this obstacle.

Furthermore, while the (FL) module forecasts the condition of the joint, it does not assess the deterioration of the joint. Accordingly, a (MC) model was developed that is capable of calculating the deterioration of the joint. It receives the joint's condition from the (FL) assessment and calculates the condition of expansion joints in next 10 years. Moreover, using this matrix, the model can calculate the cost of maintenance and repair.

Furthermore, the model constructed the transition matrix for thermal expansion joints in Egypt. This was achieved by reaching the optimum coefficients that change the condition of joints from a known state to another known state.

Transition Matrix for Thermal Expansion Joints in Egypt					
	Excellent	*Good*	*Fair*	*Poor*	*Failing*
Excellent	*0.0%*	*100.0%*	*0.0%*	*0.0%*	*0.0%*
Good	*0.0%*	*79.7%*	*20.3%*	*0.0%*	*0.0%*
Fair	*0.0%*	*0.0%*	*69.8%*	*23.5%*	*6.7%*
Poor	*0.0%*	*0.0%*	*0.0%*	*51.0%*	*49.0%*
Failing	*0.0%*	*0.0%*	*0.0%*	*0.0%*	*100.0%*

Nonetheless, there are an unlimited number of maintenance and repair strategies that can be undertaken. An optimization module was created that utilizes (GA) in order to select the maintenance plan that maximizes the ACI while meeting the available maintenance budget.

In order to test the model's accuracy real life case studies of bridges in Egypt were used. The model's output was assessed against visual inspections of two Bridge's; Elbadrasheen and Bashteel bridge. The model's output deviated an average of approximately 5% from actual bridge conditions, highlighting the accuracy as well as consistency of the model.

5.2 RECOMMENDATIONS FOR FUTURE RESEARCH

While the conducted research provides a tool for decision makers in determining the most appropriate maintenance plan, further research can be conducted as follows:

- The model currently considers the three major contributing factor that affect the joint's performance; age, temperature and ADT. Nonetheless, other factors can affect the performance of the joint, including but not limited to; types of traffic and pollution. Accordingly, further work can be undertaken in order to incorporate additional contributing factors that can ensure that the model better reflects real life conditions.
- The model is currently limited to assess individual bridge projects rather than a network of bridges. Further research needs to be conducted to expand the model such that it can be applied to multiple projects. This reflects highway agencies' decision making process, where maintenance plans should be optimized for the network in which the agency has jurisdiction, in order to prioritize the maintenance of individual bridges within an overall network.
- Other bridge elements also exist such as bearings and barriers. Accordingly, additional research can be conducted in order to model the condition, deterioration and maintenance of other elements.

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APPENDIX A

INVESTIGATION OF BRIDGE DECK EXPANSION JOINTS

“Questionnaire”

Name (Optional):

Occupation (optional):

Objective: in order to perceive a better insight to the joints performance, a field investigation and data assembly were carried out.

This questionnaire is designed to quantify the problem so as its causes and to obtain feedback from Engineers so as inspectors. Hopefully, this will provide a better understanding to the joints performance. In addition, it will serve as a future reference for bridges expansion joints assessment.

A. Which category would you choose to signpost the Expansion joint age?

	New	*Medium*	*Old*
A	*0-2*	*1-6*	*More Than 5*
B	*0-4*	*2-8*	*More Than 7*
C	*0-6*	*4-10*	*More Than 9*
D	*0-8*	*6-12*	*More Than 11*

B. How would you regard the appropriate categorization of daily traffic?

	Low	*Medium*	*High*
A	*0-100*	*70-1000*	*More than 800*
B	*0-1000*	*800-3000*	*More than 2500*
C	*0-2000*	*1800-5000*	*More than 4500*
D	*0-3000*	*2500-8000*	*More than 7500*

C. Which weather condition is responsible for expansion joint deterioration?

- □ *Wind*
- □ *Temperature*
- □ *Rain*
- □ *Dust*

D. Do you think that concrete condition influences the expansion joints?

E. Would you like to mention any reason for expansion joints deterioration?

F. Denote good, fair or Poor to the expansion joint condition of a new bridge.

Temperature / *Traffic*	*Cold*	*Warm*	*Hot*
High			
Medium			
Low			

G. Signpost good, fair or Poor to the expansion joint condition of a medium aged bridge.

Temperature / *Traffic*	*Cold*	*Warm*	*Hot*
High			
Medium			
Low			

H. Designate good, fair or Poor to the expansion joint condition of an old aged bridge.

Temperature / *Traffic*	*Cold*	*Warm*	*Hot*
High			
Medium			
Low			