The Islamic University of Gaza
High Studies Deanery
Faculty of Engineering
Civil Engineering Department
Design and Rehabilitation of Structures

الجامعة الإسلامية بغزة
عمادة الدراسات العليا
كلية الهندسة
قسم الهندسة المدنية
برنامج تصميم و تأهيل المنشآت

Expert System for Structural Evaluation of Reinforced Concrete Buildings in Gaza Strip Using Fuzzy Logic

By

Khader M. Hamdia

Supervised By

Dr. Mohammed Arafa

Dr. Mamoun Alqedra

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ABSTRACT:

Reinforced concrete has become a universally dominant construction material in the past decades. The reinforced concrete structures are often exposed to many types of damages and deteriorations due to different causes and exposure conditions during their life cycle. Gaza Strip exposed to repeated military attacks. Such attacks have caused huge destructions and damages to buildings and structures. Assessment of such structures is inherently subjected to uncertainty and ambiguity, where subjective opinions and incomplete numeric data are unavoidable.

This research presents an expert system for structural evaluation of reinforced concrete buildings in Gaza Strip with sufficient flexibility to allow an inexperienced engineer to work in the field of structural assessment. For establishing the system, the procedure incorporates combination of field observations, numerical calculations and expertise of experts.

The problem of damage assessment is a kind of multi-criteria decision-making problem, wherein decisions must be made on the weighting to be given to the different assessment criteria. In this research, the assessment criteria is studied and identified based on close visual inspections and simple measurements that do not require special testing or long-term investigation. The main adopted assessment criteria are building history, environmental conditions, structural capacity, durability, and professional involvement in construction. Each of which has levels of sub-criteria. To estimate the weights of the criteria, Fuzzy Analytical Hierarchy Process (FAHP) is utilized. According to hierarchical classification of criteria, the developed expert system performs modularized stepwise assessment. To determine the state condition of a building, the evaluation of main criteria is processed from their detailed sub-criteria, and the evaluation of these detailed criteria is processed from more detailed sub-criteria in succession.

The attributes of selected criteria are formalized quantitatively using fuzzy logic concepts with reference to building codes, former research, and properties of building materials. The inputs to the system are inspection results that are mostly linguistic variables and some numeric data concerning the selected categories for the assigned criterion. These inputs are expressed as fuzzy sets with appropriate membership values and then are combined using weighting factors and fuzzy composition. In this step-by-step way, inputs are obtained for each successive level until the answer to the highest level or originally posed problem is obtained.

Two case studies are used to verify the applicability of the designed system. The results obtained by the proposed system showed consistent conclusions with the opinion of experts. The developed system is expected to be used as an effective tool to determine the structural state of reinforced concrete buildings in Gaza strip.

ملخص البحث

كثيراً ما تتعرض المنشآت المبنية من الخرسانة لأضرار وانهيارات عديدة نتيجة لأسباب مختلفة. وفي قطاع غزة تتعرض المنشآت والمباني لهجمات عسكرية متواصلة تتسبب في دمار وأضرار هائلة. ويمكن القول أن عملية تقييم المنشآت تخضع بطبيعتها إلى عدم اليقين وإلى الغموض في كثير من الأحوال حيث لا يمكن تجنب الآراء الغير موضوعية والبيانات الغير مكتملة.

يقدم هذا البحث نظاماً خبيراً للتقييم الإنشائي للمباني الخرسانية في قطاع غزة مع مرونة كافية لتمكين المهندسين قليلي التجربة والخبرة للعمل في مجال تقييم المنشآت. وعليه فان الإجراءات اللازمة لإنشاء هذا النظام تتضمن الجمع بين الملاحظات الميدانية والمعاينة البصرية للمبنى المراد تقييمه، الحسابات الهندسية، وتجربة الخبراء من الهندسين في هذا المجال.

إن تقييم حالة الضررفي المنشأة هي مسألة صنع قرار متعددة المعايير ويجب اتخاذ القرار فيها استناداً إلى أهمية معايير التقييم المختلفة. ففي هذا البحث تم دراسة وتحديد معايير التقييم الإنشائية بناءً على المعاينة البصرية والقياسات البسيطة التي لا تتطلب إجراء اختبارات خاصة أو فحوصات على المدى الطويل. حيث تم اختيار المعايير وتقسيمها في مجموعات بطريقة هيكلية. وقد كانت المعايير الرئيسية المعتمدة: تاريخ المبنى، الظروف البيئية، قدرة التحمل الانشائية، الديمومة والمشاركة المهنية في عملية انشاء المبنى ، حيث يحتوي كل من هذه المعايير الخمسة على مستويات من المعايير الفرعية. ولتقدير أهمية وأوزان المعيايير الرئيسية والفرعية فقد تم استخدام طريقة الهيكلية التحليلية الغامضة (FAHP). وطبقاً لهذه الأوزان وللتقسيم الهيكلي المتبع فإن النظام المُصمم سوف يقوم بعمل تقييم تدريجي للمعايير وذلك لتحديد حالة المبنى الإنشائية. بحيث يتم تقييم المعايير الرئيسية الخمسة بدءاً من المعايير الفرعية التابعة لها وتقييم هذه المعايير الفرعية يكون بناءً على معايير فرعية اخرى تابعة لها. من ناحية أخرى تتشكل سمات معايير التقييم المختارة كمياً باستخدام مفهوم المنطق الغامض من خلال الرجوع إلى أكواد البناء ، الأبحاث السابقة ، وخواص مواد الخرسانة. وتمثل نتائج المعاينة البصرية والقياسات البسيطة مدخلات النظام وغالباً ما تكون متغيرات لفظية وبعض المعلومات الرقمية المتعلقة بحالة المعيار الذي يتم تقييمه.

ولإثبات فعالية النظام وامكانية تطبيقه فقد تم تجربته على حالتين دراسيتين ، حيث أظهر النظام المقترح عند تطبيقه نتائج متوافقة مع آراء الخبراء في مجال التقييم الانشائي. ومن المرجو ان يتم استخدام هذا النظام كأداة فعالة في تحديد التقييم الانشائي للمباني الخراسانية في قطاع غزة .

DEDICATION

This research is dedicated to the memories of my father,

ACKNOWLEDGMENT

I would like to express my deepest gratitude and appreciation to Dr. Mohamed Arafa and Dr. Mamoun Alqedra, for their unconditional guidance, patience, and encouragement at each step of this research.

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CHAPTER ONE:
INTRODUCTION

1.1 BACKGROUND

The assessment of existing reinforced concrete buildings will become a more frequent task for engineers in the future due to the increasing age of existing buildings, where reinforced concrete has become a universally dominant construction material in the past decades. Large numbers of existing structures need either rehabilitation or demolition due to natural or manmade causes. Natural disasters, earthquakes, wars, conflicts, etc. result normally in various sudden degrees of damages, while long neglect, abuse, environmental factors, inadequate design, and construction, etc. result in progressive deterioration. Meantime Gaza Strip is exposed to repeated military attacks, such attacks have caused huge destructions and damages to buildings and structures. Demolition of every building which does not comply with the requirement of present day loading levels or which shows signs of distress would be unthinkable both practically and economically. Structures, which suffer total or partial collapse, are easy to identify, however it is difficult to assess the structural state of the standing structures.

Expert Systems are sophisticated computer systems that store expert knowledge on specific subjects and can provide answers to questions on these subject areas. They are relatively new and can be attractive to structural engineers. An expert system is a useful tool for solving ill-defined problems in which intuition and experience are necessary ingredients. The problem of damage assessment is a typical one of ill-defined problems in the field of structural engineering. However, a number of problems arise when an expert system is built for practical use. How to treat uncertainty and ambiguity is one of the problems, which are faced occasionally. Those uncertainties or ambiguities can be handled using the theory of fuzzy sets [1, 2, 3, 4].

1.2 STATEMENT OF THE PROBLEM

The damage assessment process has features, which are difficult due to various reasons, such as; the uncertainties associated with different stages of analysis, lack of available information and the complex mechanism of structural deterioration. The state and damage assessment of structures are inherently subject to vagueness, ambiguity and consequently to uncertainty, where subjective opinion and incomplete numeric data are unavoidable. Owners and stakeholders are not satisfied with such a subjective evaluation and expect that uncertainties are made evident and not hidden. Not only, that they fear a lack of safety, but also they want an objective advice with respect to necessary monetary, material and personal expenses for a future decision of the buildings state.

In Gaza Strip, several buildings were damaged during the last war in Dec. 2008-Jan 2009. Most of them suffered structural problems in their main members (e.g. slab, beam, column, etc.). It is difficult to determine how seriously these problems can affect the structure capacity of the building. The decision making relating to defining the structural state of a building in most processes of structural evaluation of buildings is based mainly on personal interpretations of assessment team and carried out based on intuition and engineering judgement of experienced engineers. There is likelihood that a different investigator or the same investigator at a different point in time may select different decision. This leads to different opinions about number of buildings if they to be removed totally or to be repaired.

Since the condition evaluation of structures is based mainly on the expertise or expert engineers, hence applying the expertise remains difficult for the inexperienced engineers. There is a need to provide tool to transfer knowledge with practical guidance from experts and specialists to other practitioners and vice versa. This is another point that should be taken in consideration.

1.3 RESEARCH SCOPE AND OBJECTIVES

1.3.1 Scope

The undertaken research work is concerned with development of an evaluation system for the assessment of reinforced concrete building based on close visual inspections and simple measurements that do not require special testing or long-term investigation.

1.3.2 Objectives

The primary objective of the research is to develop an effective structural evaluation system for reinforced concrete buildings in Gaza Strip with sufficient flexibility to allow an inexperienced engineer to work in the field of structural assessment. At the same time, it allows an expert to contribute experience and knowledge towards improving and evolving problem solving in the field of structural assessment. The present work is motivated by a need to transfer knowledge and expertise from the technical books and experts in the domain field into the assessment of reinforced concrete buildings and to make that knowledge and expertise available to practicing engineers. More specifically, the research work is intended to achieve the following objectives:

1. Studying, identifying and prioritize the assessment criteria that influence the decision of the structural state assessment process.
2. Minimizing the effects of personal judgement of assessment team.
3. Developing an assessment system that enables inexpert engineers to work in the evaluation field.

4. Participating in enhancement and improvement of the understanding of the structural assessment of reinforced concrete buildings in Gaza strip.
5. Using fuzzy logic in developing the expert system.

1.4 METHODOLOGY

To achieve the objectives of this research, the following tasks have been applied as illustrated in the flow chart in Figure 1.1.

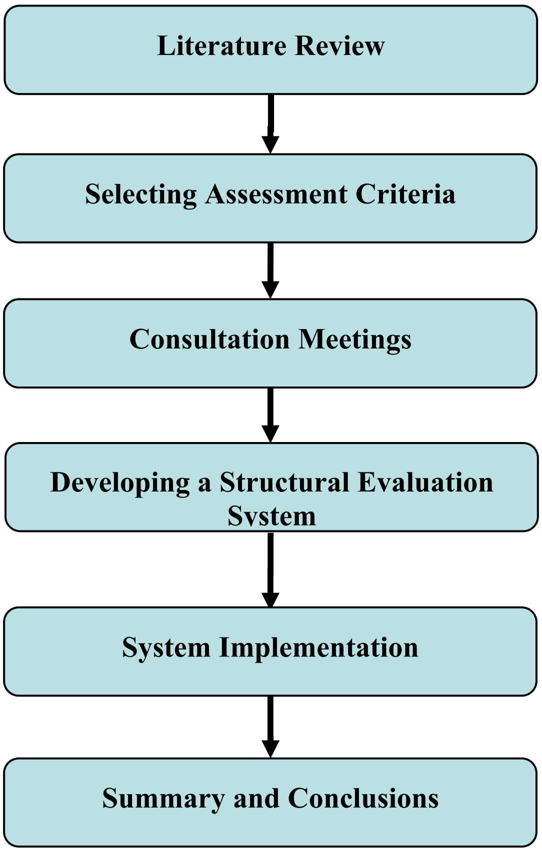

Figure 1.1: Methodology flow chart

1. Literature Review

Conducting a literature review of various research works published in literature such as books, technical papers, reports, etc. The implication of these studies on the prevailing conditions in Gaza Strip was considered.

2. Selecting Assessment Criteria

Collecting and gathering information about: the existing buildings in Gaza which need to be evaluated , the reinforced concrete structures behavior and the limits states in design codes in order to identify the assessment criteria.

3. Consultation Meetings

A set of meetings and interviews with experts in the field of damage assessment and academic professionals have been conducted, which was useful in determining the assessment criteria and its importance.

4. Developing a Structural Evaluation System

Based on the available data and using fuzzy logic, an expert system for evaluation of reinforced concrete buildings in Gaza Strip has been developed.

5. System Implementation

The proposed system was implemented on a chosen case studies in order to evaluate the applicability of the system.

6. Summary and Conclusions

At the end of the research, summary and conclusions regarding the research outcome are listed and judged.

1.5 RESEARCH OUTLINE

This research consists of six chapters as follows:

Chapter One: this chapter includes the research problem, its importance, scope, objectives, methodology and describes the research organization.

Chapter Two: (Literature Review): this chapter summarizes literature about three main topics: (1) damage assessment, (2) expert systems, and (3) fuzzy logic. This chapter considered as a global introduction to the field of expert systems in general. However, the next chapter is a very good introductory chapter to the damage assessment expert system and the proposed system approach. At the same time, this chapter includes a summary of related previous work conducted in the field of damage assessment expert system.

Chapter Three: (Damage Assessment Expert Systems) which includes; structural engineering uncertainties, approximate reasoning, and describes the characteristics of the proposed system.

Chapter Four: (Structural Assessment Criteria): That study, identifies and prioritizes the assessment criteria. Main five assessment criteria have been selected, which are building history state, environmental conditions, structural capacity, durability, and professional involvement. These criteria include several sub criteria to evaluate the structural state of the building. Meanwhile this chapter includes estimating the weights of assessment main and sub-criteria.

Chapter Five: (Designing the Structural Evaluation Expert System): that includes outline of assessment system multilevel hierarchy of assessment criteria, and evaluates the structural condition of a building. It also includes system implementation and application of case studies.

Chapter Six: (Summary and Conclusions): This chapter includes the main summary and conclusions drawn out from the undertaken research.

CHAPTER TWO:
LITERATURE REVIEW

2.1 DAMAGE ASSESSMENT

Large numbers of the existing reinforced structures need either rehabilitation or demolition due to natural or manmade causes. Natural disasters, earthquake, wars, conflicts, etc. result normally in various sudden degrees of damages, while long neglect, abuse, environmental factors, inadequate design, and construction, etc. result in progressive deterioration. Demolition of every building which does not comply with the requirement of present day loading levels or which showed signs of distress would be unthinkable both practically and economically. Therefore engineers do not only have to design new buildings, but also evaluate existing civil structures to help stakeholders in deciding if these have to be destroyed or if these can be secure.

The definitions for assessment in the International Organization for Standardization Technical Committee ISO 13822 [5] is "set of activities performed in order to verify the reliability of an existing structure for future use". It defines investigation as "collection and evaluation of information through inspection, document search, load testing and other testing". Moreover, inspection is "on-site non-destructive examination to establish the present condition of the structure".

2.1.1 Needs for Assessment and Evaluation of Existing Structures

The condition of structure needs to be evaluated for many purposes, such as; in order to determine the reliability of the structure for use, insure the adequacy of structural elements to carry their imposed loading, and to verify soundness of the whole structure. Concerns about the correct design and construction of existing structures, including low quality building material or workmanship are sometimes sufficient reasons to conduct the assessment, where spalling, cracking, and degraded surface conditions are typical indications of deterioration. In particular, serviceability and safety of existing structures need to be evaluated for a variety of reasons. Such as: changes in use or increase of loads, new regulations with higher load requirements, effects of deterioration, and damage as result of extreme loading events, unusual events (flooding, wind, earthquake, fire, bomb attack, vehicular collision, plane crash), and concern about design and construction errors and about the quality of building material and workmanship [6, 7].

2.1.2 Assessment Approaches for Reinforced Concrete Buildings

The procedures used to evaluate the structural safety and condition of existing buildings may vary depending on the behavior of the structure and the reason for the evaluation. There are numerous references describing methods for investigating the condition of a structure. These include methods presented by the International Standards Institutions e.g. American Concrete Institute (ACI), British Standards Institute (BSI), International Organization for Standardization (ISO), European Norm standards (EN1504), and European projects manuals such as CONTECVET, NORECON, REHABCON, BRIME, and others. All of these documents adopt a planned regime of investigation for existing structures with variable levels of complexity according to the situation and the structure importance [3, 8].

Most of assessment approaches are similar in principle, but vary in the details. While some approaches start from the basics, others are continuations from where a previous assessment method ended. However, most procedures incorporate the following steps: the first step; is to study the original design and construction documents and to ensure that the structure was built in accordance with them. If documents are not available, it may be necessary to make a survey to obtain measurement and details of the structural framing. The second step is to examine visually different members of the structure for their physical condition. The third step is to obtain an overall evaluation of the structural condition of the building. This may involve an analysis of the structure to determine the internal forces required in each member and a judgement of the ability of each member to resist these forces. This third step may be omitted [3].

2.1.3 Key issues of assessment Approaches

During the assessment of existing structures, it is of great importance that the procedure used is formulated to make sure that no legal difficulties arise [9]. The investigation process may involve a preliminary visual survey, followed by inspection that is more detailed and testing to determine the cause and general extent of deterioration. Depending on these findings, further investigation and testing may be required to identify specific boundaries of deterioration or potential deterioration. The information gathered during the investigations is used to provide understanding of the mechanisms that cause deterioration, the severity and extent of defects, and the implications for repair or other rehabilitation strategies [7].

Schneider [9] suggests that the key issue when assessing an existing structure is safety, and the options available for the assessing engineer are shown in Figure 2.1. A large responsibility is placed on the assessing engineer. Based on limited means and small fees, it is up to the engineer to decide whether the structure is safe to use or if additional investigations should be carried out. The consensus of a group of experts should be used as a substitute for codes, in principle; the acceptance of increased risk should be left to this team of experts [9].

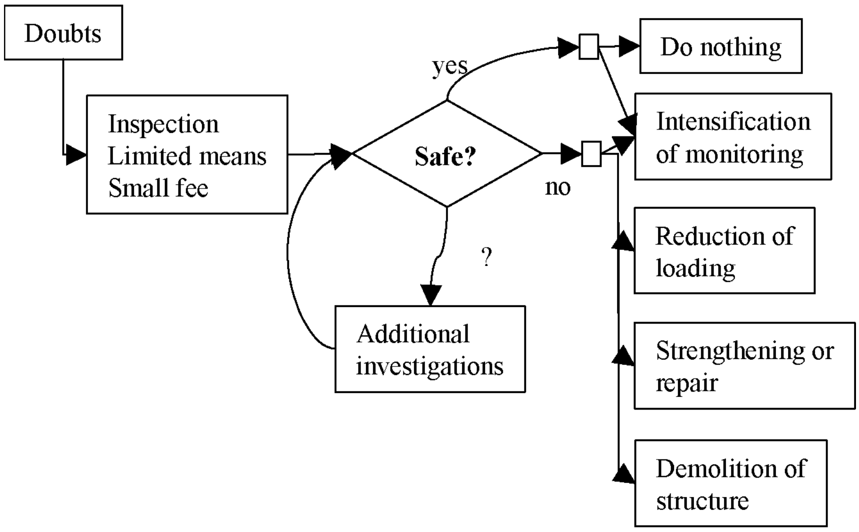

Figure 2.1: The key question for assessing engineer, (from Schneider [9]).

2.1.4 Design versus Assessment

Whereas the design of new structures is almost completely regulated by codes, there are no objective ways for the evaluation of existing facilities. Experts often are not familiar with the new tasks in system identification and try to retrieve at least some information from available documents [10].

Following the standard approach for structure design, a static system is defined and cross sections are assumed. Loads and load intensities influencing the structure are obtained from codes and load effects are calculated. The load effects are compared with the capacities of the structure and its cross section. Design equations from codes are often used, especially for calculations of resistance (e.g .load bearing capacity). If the capacity is insufficient with the assumed cross section, a change in the geometry and/or of material quality is required, and a new static system is defined. New section forces are calculated, with associated redesign of the sections. This procedure is repeated until all design requirements are fulfilled.

When assessing an existing structure, the situation is different. Loads are in many cases still adopted from codes but cross sections; geometry and material properties of the structure are available. One objective of the assessment is to verify that the load carrying capacity of the cross sections is greater than the load effects originating from the loading. Load carrying capacities are often calculated using design equations; this use of design codes for assessment purposes is debatable since design codes are developed to be generic and to fit a very large number of different situations. The fact that codes are generic suggests that the degree of utilization with respect to load carrying capacity may be low for special cases.

Another significant difference between design and assessment is that in an assessment situation, a structure exists that is available for testing. The amount of available information is greater. This means that factors such, as material strength no longer need to be generic, but can be evaluated for the specific object. Since the structure exists in reality and not only on the drawing board, it is possible to gain further information about it if necessary, thereby reducing the uncertainties in different variables [6, 7].

2.1.5 Assessment Practice in Gaza Strip

Gaza Strip is a coastal area located in the Middle East and consists of an area approximately 360 km^2. It has a temperate climate, with mild winters, dry and warm to hot summers. This environmental conditions act an important role in assessment process. Gaza Strip exposed to repeated attacks by Israeli military, the last war on December 2008-January 2009 is an example. These attacks usually result in huge deteriorations and damages in buildings and structures. In general, Buildings in Gaza Strip are low-rise reinforced concrete structures. Many of buildings are of less than five floors, though some of multistory buildings are present.

Several local institutions and consulting firms in Gaza Strip undertake studies of assessment and evaluation of the faults in existing structures. Ministry of public works and housing (MPWH) one of the governmental institutions works extensively in this field especially for building damaged because of Israeli attacks. Faculty of engineering at Islamic university in addition to Association of Engineers is another institutions work at the field. These institutions have a number of experts in assessment field. The local practice of assessment involves some or all of the following steps [8]:

1- Site visits and visual inspection
2- Measurements and surveying works
3- Assessment of soil bearing capacity
4- On site and/or laboratory testing of concrete and other building materials
5- Evaluation by experience and/or by structural analysis
6- Assessment report

Until now, there is no national standard in Palestine concerned in assessment and evaluations of existing structures with regard to their structural strength, safety, and serviceability. However, Abu Hamam [8] developed a new approach for assessment of the rehabilitation needs for existing buildings. The approach uses a planned regime of inspection and testing with efforts proportional to the cause, type, and extent of damage. It provides the outlines for assessment steps depending on the extent of damages. In particular, the decision to determine the structural state of the assessed building is referred to expert or group of expert engineers.

2.2 EXPERT SYSTEMS

2.2.1 Introduction

Expert system research, a widely used branch of artificial intelligence, mainly concentrates on tasks that can be fulfilled only by experienced, well-trained people, or in other words, by certain experts. In a broad sense, artificial intelligence is the area of computer science focusing on creating machines that can engage on behaviors that humans consider intelligent. It is concerned with making computers act more like human beings. Artificial intelligence research may be classified into seven categories as shown in Figure 2.2. These categories clearly identify separate areas of research but are closely interrelated. For example, expert system developers use artificial intelligence knowledge representation techniques and problem-solving approaches. The heuristics are usually accumulated by a human expert over a number of years. Many agree that the expert systems area has advanced furthest and achieved the most success in applying artificial intelligence methods to real-world problems [11, 12].

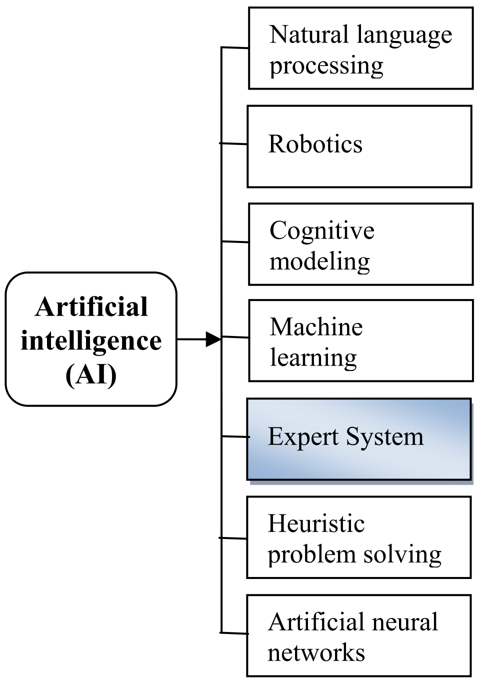

Figure 2.2: Researches in artificial intelligence (from Adeli [12])

2.2.2 Definition

Expert systems (E.S) system is a computer program, which provides the user with advice, or recommendations on the designated domain as a real expert or experts would. In such a computer program, human expertise in the designated domain is well represented and saved in the form of a knowledge base. It is also referred to as knowledge based expert systems (KBES), decision support systems, intelligent systems, or smart systems.

The definition of expert system often states that there is a heuristic component, which can operate on or use knowledge to make recommendations, draw conclusions, and/or propose a hypothesis. This integration not only helps to preserve the human expertise but also allows humans to be freed from performing the more routine activities that might be associated with interactions with a computer-based system. Given the number of textbooks, journal articles, and conference publications about expert systems and their application, it is not surprising that there exist a number of different definitions.

Feigenbaum [11], one of the earliest developers, defines an expert system as "An intelligent computer program that uses knowledge and inference procedures to solve problems that are difficult enough to require significant human expertise for their solution". Webster's dictionary defines expert system as [14]: "Computer software that attempts to mimic the reasoning of a human specialist". Whereas it defines an expert as "One with the special skill or mastery of a particular subject". By these definitions, it is shown that the focal point in the development of an expert system is to acquire and represent the knowledge and experience of a person(s) who have been identified as possessing the special skill or mastery [17].

2.2.3 Expert Systems versus Conventional Programs

Most of conventional computer programs treat problems with algorithmic nature. They are not able to solve the problems that rely on engineering judgement effectively. Further, these programs were developed by different universities or institutions, which did not provide a unified strategy so that they can exchange information and knowledge among. Expert systems can overcome the problems faced by traditional programs. The main difference between expert system and conventional programs is that expert systems can explain how to resolve the problems, where this property is not found in conventional programs since they depend on the iterative calculations only. Another one is that, the expert systems are characterized by a knowledge base separated from the machine inference, which opposite to conventional programs. Expert systems can give more than one solution to one problem. In the case of traditional programs, it gives only one solution to the problem [15]. However, the following differences may be found between traditional computer programs and expert systems [12]:

1. Expert systems are knowledge-intensive programs.
2. Expert systems use heuristics in a specific domain of knowledge in order to improve the efficiency of search.
3. In an expert system, expert knowledge is usually divided into many separate independent rules or entities. The knowledge representation is transparent i.e. rather easy to read and understand.
4. The knowledge base used in an expert system is usually separated from the methods for applying the knowledge to the current problem. These methods are referred to as the inference mechanism.

5. Expert systems are usually highly interactive.
6. The output of an expert system can be qualitative rather than quantitative.
7. Expert systems tend to mimic the decision-making and reasoning process of human experts. They can provide advice, answer questions, and justify their conclusions.

2.2.4 The Need for Expert Systems

Expert systems are necessitated by the limitations associated with conventional human decision-making processes, including [16]:

1. Human expertise is very scarce.
2. Humans get tired from physical or mental workload.
3. Humans forget crucial details of a problem.
4. Humans are inconsistent in their day-to-day decisions.
5. Humans are unable to comprehend large amounts of data quickly.
6. Humans are unable to retain large amounts of data in memory.
7. Humans are slow in recalling information stored in memory.
8. Humans are subject to deliberate or inadvertent bias in their actions.
9. Humans can deliberately avoid decision responsibilities.
10. Humans lie, hide, and die.

2.2.5 Advantages and Limitations

Expert systems for applications are most useful where the knowledge can be represented in a narrow and well-defined knowledge domain. However, it offers a means of capturing human expertise, and provides an environment, which allows that knowledge to improve and expand. The advantages of expert systems are [11, 12]:

1. Knowledge is more explicit, accessible, and expandable. One can find a similarity between expert systems and the human reasoning process.
2. The knowledge base can be developed gradually and incrementally over an extended period of time. The modularity of the system allows continuous expansion and refinement of the knowledge base.
3. An expert system is not biased and it does not make cursory or irrational decisions. It uses a systematic approach for finding the answer to the problem.

Although expert systems have many advantages, the following limitations may be noted for expert systems [11, 12, 15]:

1. They do not possess the ability to learn.
2. They lack common sense and intuition.
3. The stored knowledge in expert systems in general is limited where it is represent the expertise of one expert or little number of experts in specific domain.

2.2.6 Development

The development of an expert system follows much the same path of any other software product. However, within the development of an expert system terminology and the nature of the software development process are different from conventional software systems. The major development effort in creating an expert system is the design and development of the knowledge base. One of the problems with the design and development is the lack of a formal methodology. Formal methodology means a strategy that allows to measure (precisely) the performance of an expert system similar to conventional software system design and development.

The first activity within the development life cycle of an expert system is to define the problem. Where, it is the most critical step in software development and scientific research, especially in the area of knowledge engineering. Finding a problem of the proper scope is especially imprint. A good problem to solve is one that is cognitive in nature and sufficiently complex, and has been shown to be an important function provided by only one person (or a small group) frequently [17].

The knowledge-base component of an expert system contains what is known about the subject area. It is an external file that contains knowledge and facts about the domain of the problem. Acquisition of this knowledge is the second step in the development process. It represents the process of acquiring knowledge and gets it into a computer program. Two major sources exist for the knowledge: human expert(s) and documents or text. Both sources have advantages and disadvantages. Experts tend to be more current and have a broader range of knowledge than documents. However, they may not be able to explain the reasoning behind their knowledge or beliefs, their time is expensive and unless they support the project, they can work against the goals of the expert systems development. In some cases, expertise may have been lost, and the developer must rely on documents. Documents are generally cheaper to acquire and use. However, they have limited amounts of information and what they have is not always completely relevant [11].

When the knowledge is acquired the knowledge engineers has to deal with it. The major objective in this phase is to represent the knowledge into machine-readable form. The process of acquiring knowledge from an expert and representing this knowledge into computer software are shown in Figure 2.3. Rules and frames are the most two popular ways for knowledge representation in which knowledge is stated in a deterministic state. These two methods considered knowledge representation strategies under conditions of certainty. How to treat uncertainty and ambiguity is one of the problems, which are faced occasionally. Consequently, there is a need to a method for representing problem solving knowledge under conditions of uncertainty. Despite considerable research activity, reasoning under uncertainty remains difficult because of the desire for both rigorous and easy to apply methods.

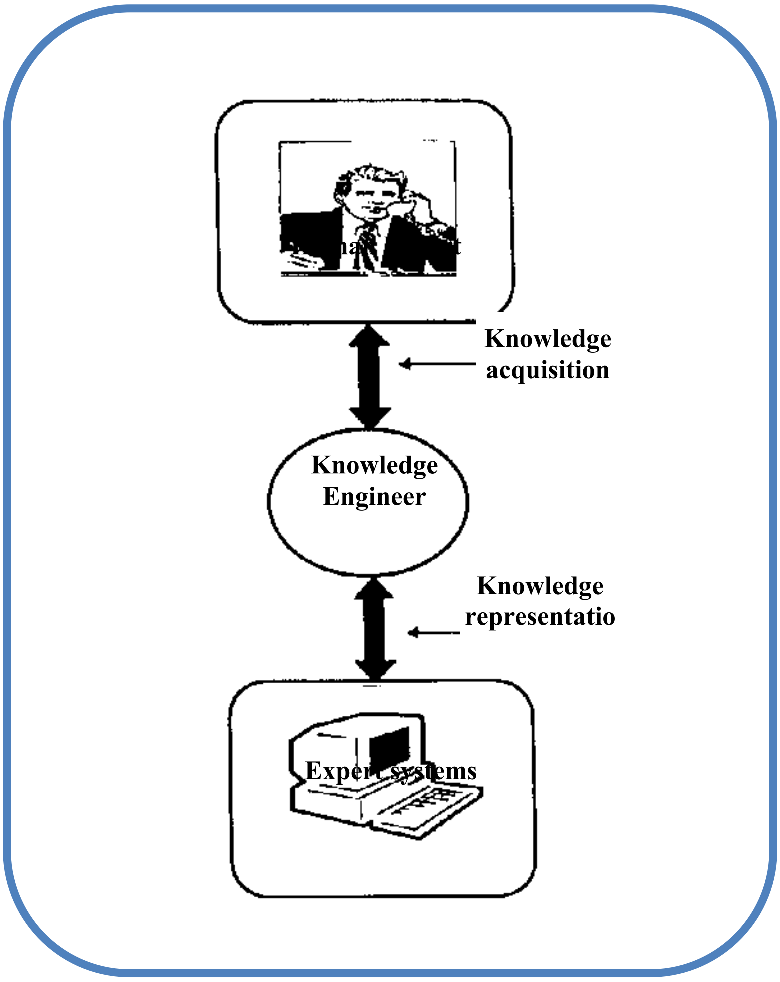

Figure 2.3: Acquiring and representation of knowledge (from Berrais [15])

There are several approaches used to uncertainty management for expert systems. They are similar in concept but vary somewhat in techniques. The best-known and used methods in existence are; Bayesian inference, Certainty factors and Fuzzy set. Discussion the advantages and disadvantages of each approaches is beyond the scope of our concerns here. However, fuzzy set theory is one of the major approaches used to handle uncertainties or ambiguities arise due to the use of linguistic terms in expert system. Fuzzy set theory is discussed deeply in section 2.3 [3, 17].

The implementation step is the process of taking the knowledge that has been acquired and represented and then put it into machine-readable format. That is, actually taking the knowledge and putting it into some computer code. Testing and evaluation of the software system is an important step of expert system development effort to ensure correctness of the outputs and user satisfaction with the product in solving the given problem. In many times much of the knowledge in an expert system is (or potentially can be) changing constantly and these knowledge units need to be updated [17].

2.3 FUZZY LOGIC

2.3.1 Introduction

Professor Lofti Zadeh [13] first introduced fuzzy logic in 1960's. This theory provides a major newer paradigm in modeling and reasoning with uncertainty. It provides the opportunity for modeling conditions that are imprecisely defined. However, in the form of approximate reasoning, fuzzy techniques provide decision support and expert systems with powerful reasoning capabilities. Fuzzy theory represents the uncertain state of the real world as it is. In another words it accounts for the real-world gradient that exists between true and false [13, 18]. The concept of fuzzy set theory has important applications in the field of knowledge based expert systems as it permits not only a mathematical treatment of transition properties (i.e., safe to unsafe; allowable stress (deformation) to unsatisfactory stress (deformation); etc.) and linguistic terms, but also operations simulating human inferences about complex interactions between variables that are not functionally related [3].

2.3.2 Definition

The word "fuzzy", according to the Oxford English Dictionary, is defined as "blurred, indistinct, imprecisely defined, confused vague", however in engineering problem this definition should be disregarded and the word "fuzzy" have to be viewed as a technical adjective [19]. Webster's dictionary [14] defines a fuzzy logic as: "a system of logic in which a statement can be true, false, or any of a continuum of values in between". It also defines fuzzy set as "a mathematical set with the property that an object can be a member of the set, not a member of the set, or any of a continuum of states of being a partial member of the set".

As the definitions imply, fuzzy logic theory is not a fuzzy theory but it is logic interpret the fuzziness. Essentially, what should be emphasized is that although the phenomena that the fuzzy theory characterizes may be fuzzy, the theory itself is precise. In other words, fuzzy theory itself is precise; and the "fuzziness" appears in the phenomena that the theory tries to study [19].

2.3.3 Fuzzy Sets and Membership Functions

The permissiveness of fuzziness in the human thought process suggests that much of the logic behind thought processing is not traditional two-valued logic or even multivalued logic. A fuzzy set is an extension of a crisp set. Crisp sets allow only full membership or no membership at all, whereas fuzzy sets allow partial membership. Instead of an element being 100% true or false, fuzzy logic deals with degrees of membership and degrees of truth, instead of yes and no. Something can be partially true and partially false at the same time. Figure 2.4 shows how fuzzy Logic implements a gradient of possible states as opposed to a binary one or zero [18, 20].

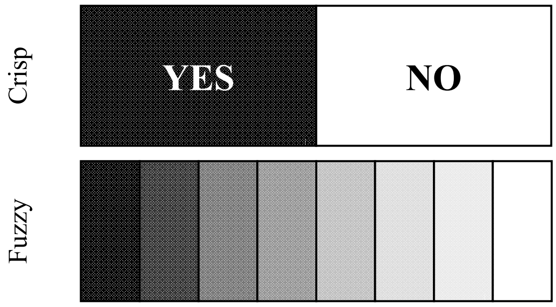

Figure 2.4: Crisp and fuzzy logic

By mathematical definition, a crisp set is a collection of distinct (precisely defined) element. It can be superset containing other crisp sets. A superset will represent the universe of discourse if it defines the boundaries in which all elements reside. An element either belongs to a set or not. If the set under investigation is A, testing of an element x using characteristic function χ is expressed as

$$\chi_A(x) = \begin{Bmatrix} 1 & x \in A \\ 0 & x \notin A \end{Bmatrix} \quad (2\text{-}1)$$

Methods based on classical set theory are utilized mainly in areas where measurements can be made very precisely. However, when such favorable conditions are not reflected in the domain of the problem, the application of classical set theory does not yield good results. On the other hand, in linguistic terms sets, there are sets that cannot be considered as crisp. As an example, one can consider the sets of "good" and "bad": Since the limits of such sets cannot be defined with precision, one can be considered as belonging to both of them, at least in a certain measure. Fuzzy logic allows us to consider such aspects. It can represent commonsense linguistic labels like slow, fast, small, large, heavy, low, medium, high, tall, etc.

Fuzzy set theory extends the concept of crisp theory by defining partial membership. In contrast to crisp sets, a fuzzy set is a collection of distinct elements with varying degree of relevance or inclusion. The characteristic function test no longer has a trivial role because it determines the degree of relevance or inclusion. The characteristic function, which here is known as membership function, can take interval values between 1 and 0. The fuzzy set A can be expressed as a set of ordered pairs. Each pair consists of an element x and its grade of membership function as;

$$A = \{(x, \mu_A(x))\} \quad (2\text{-}2)$$

In the classical set theory, an entity is the member of a set or not. Because of the uncertainty of an entity in a fuzzy set, membership function that is the cornerstone of the fuzzy sets needs to be defined for each entity in the set [18, 19, 20].

2.3.4 Membership Functions Shapes

There are different shapes of membership functions. The most often used functions in fuzzy sets are: (1) Piecewise linear (triangular and trapezoidal), (2) Quadratic, (3) Gaussian according to the formula $\mu(x) = \exp\ (-(x-\mu)/\sigma)^2)$, (4) Some special functions. They are shown in Figure 2.5

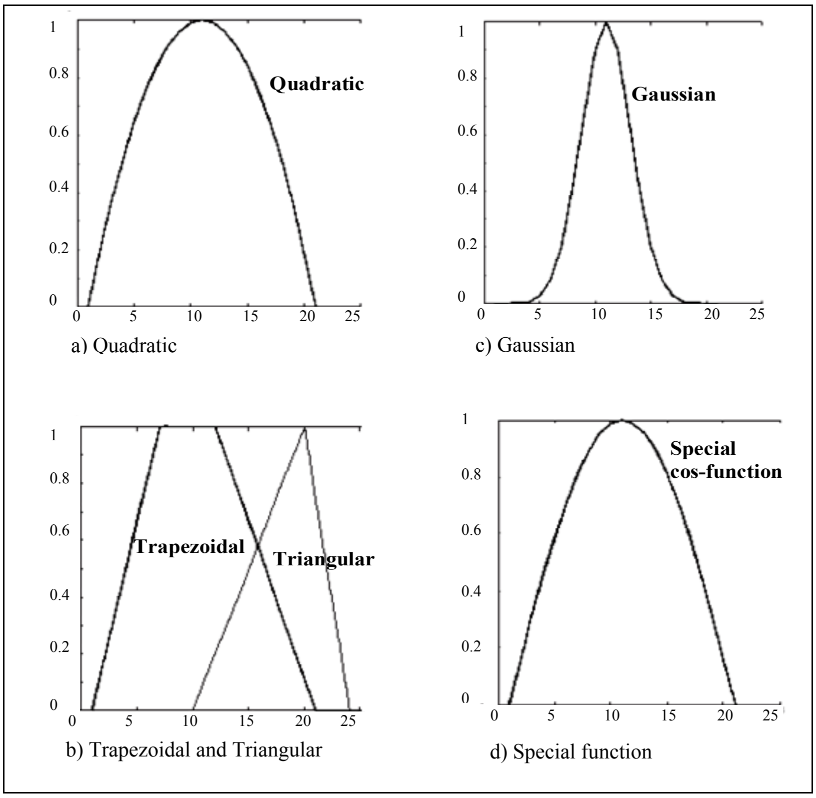

Figure 2.5: The most commonly used membership functions (from Reznik [21])

Triangular or trapezoidal (piecewise linear) functions have proved to be more popular with fuzzy logic theoretic and practitioners rather than higher order based functions such as quadratic, cubic, etc. A possible reason for this is simplicity of this function often allowing for the prediction and calculation of an output of the fuzzy system. Another reason is that the extra smoothness introduced by higher order fuzzy sets and demanding higher computational consumption is not strongly reflected in the output quality of a fuzzy model [20, 21].

2.3.5 Fuzzy numbers

A fuzzy number is a special fuzzy set $A = x \in R | \mu_A(x)$ where x takes its values on the real axis $R: -\infty < x < +\infty$ and its membership Function μ_A is a continuous mapping from and to the close interval [0, 1].

The most commonly used fuzzy numbers are triangular and trapezoidal fuzzy numbers as shown in Figure 2.6. Triangular fuzzy numbers have been used extensively in different applications, because of its simplicity. Its membership function is

$$M(x)=\begin{cases}0 & x<l \ or \ x>u \\ (x-l)/(m-l) & l\le x\le m \\ (u-x)/(u-m) & m\le x\le u\end{cases} \qquad (2\text{-}3)$$

However, trapezoidal fuzzy numbers are another special classes of fuzzy numbers often used in practice. The trapezoidal membership function is

$$M(x)=\begin{cases}0 & x>d \ or \ x<a \\ (x-a)/(b-a) & a<x<b \\ 1 & b<x<c \\ (d-x)/(d-c) & c<x<d\end{cases} \qquad (2\text{-}4)$$

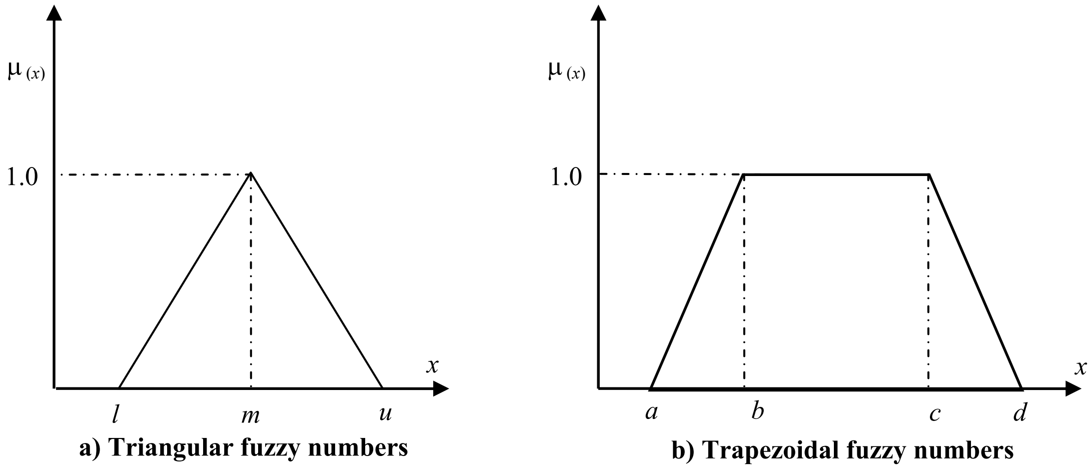

Figure 2.6: Special classes of fuzzy numbers

2.3.6 Linguistic Variables and Hedges

In linguistics, fundamental atomic terms are often modified with adjectives (nouns) or adverbs (verbs) like very, low, slight, more or less, fairly, slightly, almost, barely, mostly, roughly, approximately, and so many more that it would be difficult to list them all. These modifiers called ''linguistic hedges'' :that is, the singular meaning of an atomic term is modified, or hedged, from its original interpretation [20]. A linguistic variable is one with a value that is a natural language expression referring to some quantity of interest. It differs from a numerical variable in that its values are not numbers but words or sentences in a natural or artificial language. Since words, in general, are less precise than numbers, the concept of a linguistic variable serves the purpose of providing a mean of approximate characterization of phenomena which are too complex or too ill-defined to be amenable to description in conventional quantitative terms. These natural language expressions are then in turn names for fuzzy sets composed of the possible numerical values that the quantity of interest can assume. Fuzzy sets theory operates just with mathematical models as any other mathematical theory does. It replaces one sort of mathematical model with another one. However, fuzzy sets theory allows us to model words and terms of natural language with the help of linguistics variables [20, 21].

2.3.7 Fuzzy Logic Systems

Figure 2.7 depicts a fuzzy logic system that is widely used. A fuzzy logic system maps crisp inputs into crisp outputs. It contains four components fuzzifier, rules, inference engine and defuzzifier. Once the rules have been established, a fuzzy logic system can be viewed as a mapping from inputs to outputs.

Fuzzification is the process of making a crisp quantity fuzzy. Simply this is done by recognizing that many of the quantities, which are considered crisp and deterministic, are actually not deterministic at all. They carry considerable uncertainty. If the form of uncertainty happens to arise because of imprecision, ambiguity, or vagueness, then the variable is probably fuzzy and can be represented by a membership function. On the other hand, rules may be provided by experts or can be extracted from numerical data. In either case, engineering rules are expressed as a collection of IF-THEN statements. Each rule contains one or clauses in the IF part of the rule, these clauses are known as the antecedent, and one (but potentially more than one) clause in the THEN part of the rule, these clauses collectively are called the consequent. The fuzzy inference engine combines rules into a mapping from fuzzy sets in the input space to fuzzy sets in the output space based on fuzzy logic principles

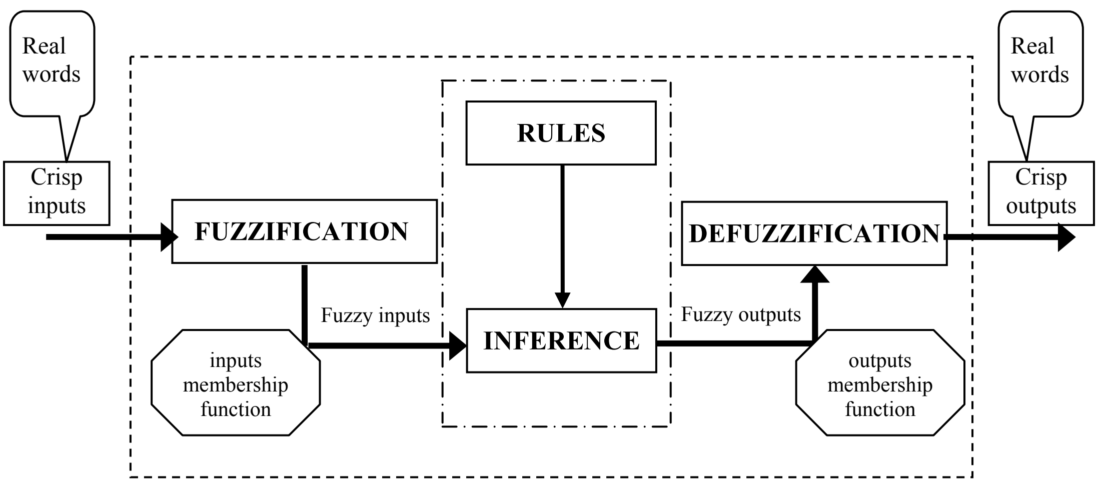

Figure 2.7: Block diagram of fuzzy logic system

Defuzzification is the conversion of a fuzzy quantity to a precise quantity, just as fuzzification is the conversion of a precise quantity to a fuzzy quantity. The output of a fuzzy process can be the logical union of two or more fuzzy membership functions defined on the universe of discourse of the output variable. In other words, the fuzzy logic system works mainly in four processes: Fuzzification, which is the process of taking actual real-world data (such as temperature, costs, damage, strength, speeds, etc.) and converting them into a fuzzy input. The end goal of any fuzzy logic system is to produce a real world output without having to go through a large and complex system. Therefore, fuzzy systems usually take multiple real world inputs, fuzzify these inputs, and produce a single real world output via Defuzzification. In order to get to the defuzzification step, the fuzzy inputs must be evaluated against a set of Rules, that are combined by the Inference [19, 20].

2.3.8 Fuzzy Analytic Hierarchy Process (FAHP)

Multi criteria analysis appeared in the 1960's as a decision-making tool. It is a discipline aimed at supporting decision makers faced with making numerous and conflicting evaluations. Specifically it aims at highlighting these conflicts and deriving a way to come to a compromise in a transparent process. There are many techniques used for multi criteria analysis. Analytic Hierarchy Process (AHP) is one of the well-known Multi-criteria decision making techniques that was first proposed by Saaty [42]. AHP preferences are determined by making pair-wise comparisons. These comparisons are made using a preference scale, which assigns numerical values to different levels of preference. The standard preference scale used for AHP is 1 to 9 scale, which lies between "equal importance" to "extreme importance". While sometimes, different evaluation scales can be used such as 1 to 5. The classical AHP takes into consideration the definite judgments of decision makers. Though the classical AHP includes the opinions of experts and makes a multiple criteria evaluation, it is not capable of reflecting human's vague thoughts and thinking style. Experts may prefer intermediate judgments rather than certain judgments. The fuzzy set theory makes the comparison process more flexible and capable to explain experts' preferences. Therefore, Fuzzy Analytic Hierarchy Process AHP (FAHP), which is a fuzzy extension of AHP, was developed to solve the hierarchical fuzzy problems [22, 23, 24].

Chang [25] developed FAHP in 1992 to solve the hierarchical fuzzy problems. Chang in his extension depends on the degree of possibilities of each criterion. According to the responses on the question form, the corresponding triangular fuzzy values for the linguistic variables are placed and for a particular level on the hierarchy, the pairwise comparison matrix is constructed.

Sub totals are calculated for each row of the matrix and new (l, m, u) set is obtained, then in order to find the overall triangular fuzzy values for each criterion, $l_i/\Sigma l_i$, $m_i/\Sigma m_i$,

$u_i/\Sigma u_i$, (i=1, 2,..., n) values are found and used as the latest M_i (l_i, m_i, u_i) set for criterion M_i in the rest of the process. In the next step, membership functions are constructed for the each criterion and intersections are determined by comparing each couple. In fuzzy logic approach, for each comparison the intersection point is found, and then the membership values of the point correspond to the weight of that point. This membership value can also be defined as the degree of possibility of the value. For a particular criterion, the minimum degree of possibility of the situations, where the value is greater than the others, is also the weight of this criterion before normalization. After obtaining the weights for each criterion, they are normalized and called the final importance degrees or weights for the hierarchy level.

To apply the process, according to the method of Chang's extent analysis, each criterion is taken, and extent analysis for each goal g_i is performed, respectively. Therefore, m extent analysis values for each criterion can be obtained, with the signs: $M^1_{gi}, M^2_{gi}, \ldots\ldots. M^m_{gi}$, $i = 1,2,3 \ldots n$, where g_i is the goal set (i=*1, 2, 3, 4, 5, ...n*) , and all the $M^j_{gi}\,(j = 1,2,3 \ldots.. m)$ are triangular fuzzy numbers (TFNs). Refer to section 2.3.5.

The steps of Chang's extent analysis can be given as in the following:

Step 1: The value of fuzzy synthetic extent (Si) with respect to the i^{th} criterion is defined as

$$S_i = \sum_{j=1}^{m} M^j_{gi} \otimes \left[\sum_{i=1}^{n} \sum_{j=1}^{m} M^j_{gi} \right]^{-1} \qquad (2\text{-}5)$$

To obtain $\sum_{j=1}^{m} M^j_{g_i}$ perform the "fuzzy addition operation" of m extent analysis values for a particular matrix such that

$$\sum_{j=1}^{m} M^j_{gi} = \left(\sum_{j=1}^{m} l_j , \sum_{j=1}^{m} m_j , \sum_{j=1}^{m} u_j \right) \qquad (2\text{-}6)$$

and to obtain $\left[\sum_{i=1}^{n} \sum_{j=1}^{m} M^j_{gi} \right]^{-1}$ the "fuzzy addition operation" of $M^j_{gi}\,(j = 1,2,3 \ldots\ldots. m)$ values is performed such as:

$$\sum_{i=1}^{n} \sum_{j=1}^{m} M^j_{gi} = \left(\sum_{i=1}^{n} l_i , \sum_{i=1}^{n} m_i , \sum_{i=1}^{n} u_i \right) \qquad (2\text{-}7)$$

and then the inverse of the above vector is computed in Equation. (2-8) such as:

$$\left[\sum_{i=1}^{n} \sum_{j=1}^{m} M^j_{gi} \right]^{-1} = \left(\frac{1}{\sum_{i=1}^{n} u_i}, \frac{1}{\sum_{i=1}^{n} m_i}, \frac{1}{\sum_{i=1}^{n} l_i} \right) \qquad (2\text{-}8)$$

Step 2: As M_2 and M_1 are two triangular fuzzy numbers, the degree of possibility of $M_2 = (l_2, m_2, u_2) \geq M_1 = (l_1, m_1, u_1)$ is defined as

$$V(M_2 \geq M_1) = \sup_{y \geq x} \left[\min \ (\mu_{M1}(x), \mu_{M2}(y)) \right] \qquad (2\text{-}9)$$

This expression can be equivalently written as given in Equation (2-10) below

$$V(M_2 \geq M_1) = \begin{cases} 1, & if, m_2 \geq m_1, \\ 0, & if, l_1 \geq u_2, \\ \dfrac{l_1 - u_2}{(m_2 - u_2) - (m_1 - l_1)}, & otherwise, \end{cases} \quad (2\text{-}10)$$

Equation (2-10) is illustrated in Figure 2.8 where d is the ordinate of the highest intersection point of the two fuzzy numbers i.e. intersection point between μ_{M1} and μ_{M2}. To compare M_2 and M_1, we need both values of $V(M_2 \geq M_1)$ and $V(M_1 \geq M_2)$.

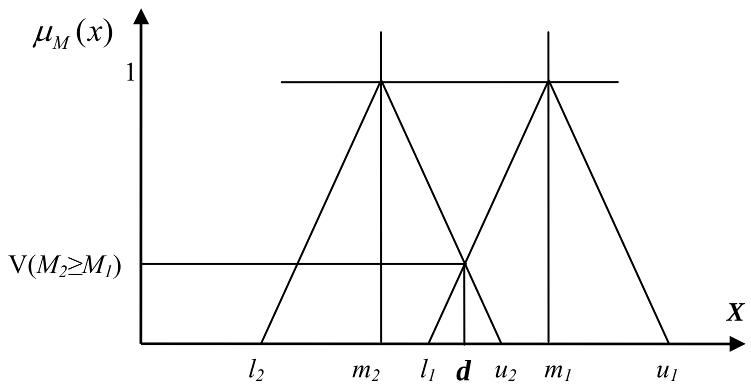

Figure 2.8: The Intersection between two triangular fuzzy numbers

<u>Step 3</u>: The degree of possibility for a convex fuzzy number to be greater than k convex fuzzy numbers $M_i (i = 1,2,3.......k)$ can be defined by:

$$V(M \geq M_1, M_2, ...M_k) = V[(M \geq M_1) \text{ and } (M \geq M_2).....\text{and } (M \geq M_k)] = \min V(M \geq M_i) \quad (2\text{-}11)$$

$, i = 1,2,3,.....k$

Assume that

$$d'(A_i) = \min V(S_i \geq S_k) \quad (2\text{-}12)$$

For $k = 1,2,3,.....n, \; k \neq i$

Then the weight vector is given by

$$W' = (d'(A_1), d'(A_2)...., d'(A_n))^T \quad (2\text{-}13)$$

where $A_i (i = 1,2,3,.....n)$ are n elements.

<u>Step 4</u>: Via normalization, the normalized weight vectors are

$$W = (d(A_1), d(A_2)...., d(A_n))^T \quad (2\text{-}14)$$

where W is a non-fuzzy number.

2.4 PREVIOUS WORKS

In the literature, several researches and wide range applications have been developed for concrete design, condition assessment, repair, and rehabilitation of concrete structures using knowledge-based expert systems. Advances in computer hardware technology and software development made it feasible to develop expert systems that are an effective decision-making tool for condition evaluation of reinforced concrete buildings. In the last few years, the use of knowledge based computer programs in structural engineering applications has significantly advanced. The application of expert systems in this area is growing rapidly because of enhanced durability thereby reducing maintenance and repair costs, the loss of highly qualified engineers and advances in data-gathering methods [12, 27].

Several common computer programs or software has been developed to provide a means for an engineer to use expert systems in the diagnosis of structural damage problems. Adeli [12] presented several expert systems in civil engineering including structural and construction engineering for a satisfactory solution to the problems of diagnosis, fault detection, prediction, monitoring, planning and design. A survey of many of the existing prototypes and operational expert systems developed for the construction industry has been presented by Kaetzel and Clifton [11]. Another effort by Furuta, et al. [2] reviewed and examined a several expert systems at various stages of development in structural engineering. In addition, attempts are being made to apply expert systems to both the safety evaluations of structures during construction and the choice of methods for constructing bridge structures. Furuta, et al. [1] attempt to develop a knowledge-based expert system for assessing damage states of bridge structure, where the focus is put on reinforced concrete bridges deck that system consists of a rule-base, working memory and interpreter. A study of fuzzy based state assessment for reinforced concrete building structures by Kim et al. [4], who estimates the current state of buildings and presents a guide for future maintenance and management. A Choquet fuzzy integral is used to integrate the estimated results of the criteria and their weights expressed as a Sugeno λ-fuzzy measure .As a result of integration, the system provides a state index, which is used to determine recommended actions for future maintenance and management. Lu and Simmonds [3] proposed a methodology for developing a knowledge-based expert system for assessing the structural condition of existing reinforced concrete framed buildings. The procedure incorporates the results of field observations and, strength computations of individual members and combines these using weighting factors to obtain the overall structural condition. However, an effort is made by Anoop, et al. [30] to use the ability of fuzzy sets in handling uncertainties for evolving a general methodology for durability-based service life design of reinforced concrete structural members. Sasmal and Ramanjaneyulu [41] developed a systematic procedure and formulations for condition evaluation of existing bridges using Analytic Hierarchy Process in a fuzzy environment.

CHAPTER THREE:
DAMAGE ASSESSMENT EXPERT SYSTEMS

3.1 INTRODUCTION

The damage assessment of structures is not an easy task due to the lack of available information and the complex mechanism of structural deterioration. The state and damage assessment of structures are inherently subject to vagueness, ambiguity and consequently to uncertainty, where subjective opinion and incomplete numeric data are unavoidable. Following a strong earthquake, or war, the few structures, which suffer total or partial collapse, are easy to identify. For most structures, which remain standing, however, it is difficult to assess their damage state.

The traditional procedure for evaluating buildings consists of a number of steps, each of which requires considerable experience and judgement on the part of the investigating engineers. Therefore, especially after major natural or man-made disasters, such as an earthquake when there may be buildings requiring immediate evaluation; it is desirable to have a simple but reliable method of assisting the structural engineer. In evaluating the state of reinforced concrete buildings process, it is necessary to develop a methodology for combining field observations, numerical calculations and structural expertise. In many instances, it is desirable to give a mathematical significance to the results of visual observations that are often expressed in linguistic terms [1, 3, 4].

Expert Systems are relatively new and can be attractive to structural engineers. An expert system is a useful tool for solving ill-defined problems in which intuition and experience are necessary ingredients. The problem of damage assessment is considered a typical one of ill-defined problems in the field of structural engineering.

3.2 UNCERTAINTIES IN STRUCTURAL ENGINEERING

The nature of uncertainty in a problem is a very important point that engineers should ponder prior to their selection of an appropriate method to express the uncertainty. From the engineering point of view, a structural problem can be considered as ‘‘uncertain’’ when lack of knowledge exists regarding the theoretical model that describes the structural system and its behavior. To overcome such uncertainties, structural engineers always base their choices on the experience accumulated in the course of time. The uncertainties associated to physical phenomena may be derived from several and different sources as shown in Figure 3.1. In the common language, something is uncertain when it assumes random meanings or behaviors (randomness), or when it is not clearly established or described (vagueness), or when it may have more than one possible meaning or status (ambiguity), or, finally, when it is described on the basis of too limited amount of information (imprecision). At a closer examination, randomness, vagueness, ambiguity, and imprecision denote uncertainties with different and specific characteristics. For randomness, the source of uncertainty is due to factors related to the physics of the phenomena, which determine the events under investigation. In other cases, the source of uncertainty arises from the limited capacity of our formal languages to describe the engineering problem to be solved (ambiguity) or from incorrect and/or ill-posed definitions of quantities, which convey some informative content (vagueness), or from some lack of knowledge (imprecision) [20, 26].

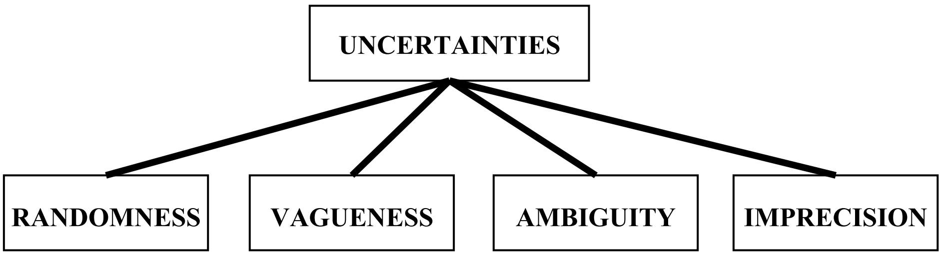

Figure 3.1: Uncertainties sources

A very good classification of uncertainty with respect to its types and characteristics respectively has been presented in Figure 3.2 [10].

In damage assessment process the uncertainties arises due to the use of linguistic terms for defining the building conditions state and quality of construction. While there are several techniques for handling uncertainties arising from randomness, imprecision, vagueness, ambiguity etc., fuzzy sets are commonly used for handling uncertainties associated with linguistic concept. It provides a mathematical way to represent vagueness and fuzziness in humanistic systems.

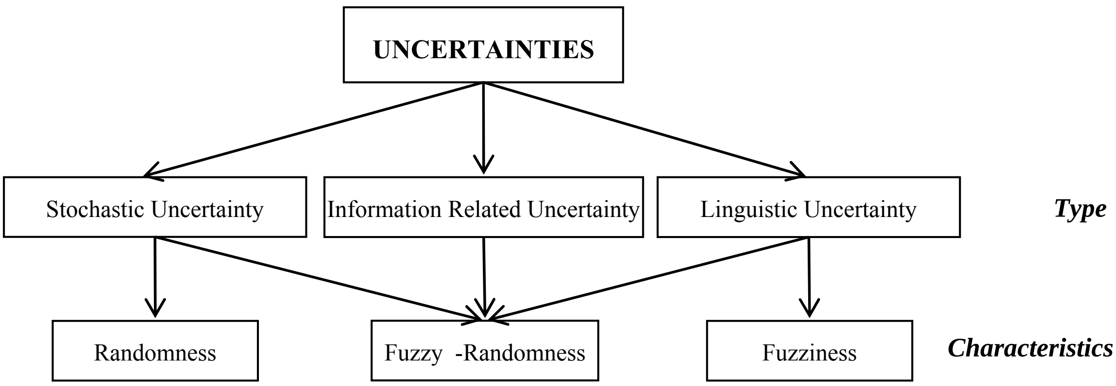

Figure 3.2: Uncertainty classification with respect to type / characteristics (from Faust [10])

3.3 APPROXIMATE REASONING

The assessment of damage to a structure is a difficult process requiring significant human judgement. This process is complicated by the fact that the information needed to make a damage assessment with high confidence is incomplete and involves uncertainty. Evaluation of the situation becomes even more difficult when one realizes that the uncertainties encountered include both random and nonrandom kinds of data. Because of a lack of complete understanding of the real problem, the typical analysis of the damaged structure would simply be assigned to one of two groups survival or failure. If we take a closer look at the problem, however, we see that it is not a two-class problem, but rather is a continuous on. There is overlap between different damage levels such as; No damage, Slight damage, Moderate damage, Sever damage and Very extensive damage, as in Figure 3.3. It is this lack of crispness (or inherent fuzziness) in the problem that causes difficulty, first in determining the damage level, and second, in deciding on an acceptable level of damage [12].

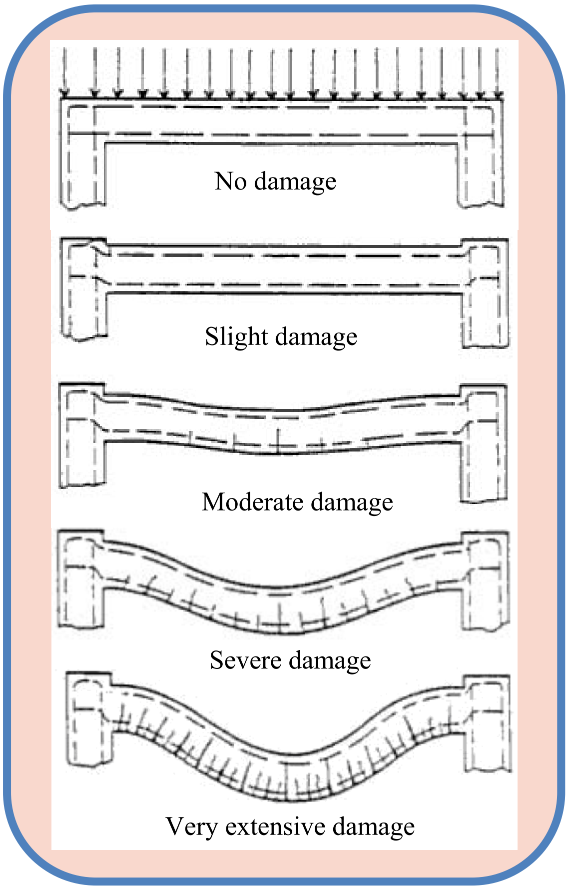

Figure 3.3: Description of damage levels (from Adeli [12])

The ultimate goal of fuzzy logic is to form the theoretical foundation for reasoning about uncertain propositions; such reasoning has been referred to as approximate reasoning. Approximate reasoning is analogous to classical logic for reasoning with precise propositions, and hence is an extension of classical propositional calculus that deals with partial truths.

For many problems two distinct forms of problem knowledge exist: 1) objective knowledge; which is used all the time in engineering problem formulations (e.g., mathematical models), and 2) subjective knowledge, which represents linguistic information that is usually impossible to quantify using traditional mathematics (e.g., rules, expert information, design requirements). The process of damage assessment is a cause and effect situation . The 'cause' usually involves engineering quantities such as stresses and strains, while the 'effect' involves subjective information concerning the functionality and repair-ability of the structure. Although there is objective information available to the expert in the form of test data and model simulations, the question of damage assessment is strongly tied to expert judgement. Thus, the quality of the assessment process is highly dependent on an expert's knowledge of the actual situation under study. The evaluation of linguistic damage states such as light, medium, and severe damage can differ from one expert to another. Moreover, the damage ranges naturally overlap, i.e, damage does not change abruptly from light to medium and from medium to severe upon reaching certain crisp thresholds. Other factors such as scarcity of data and the need to extrapolate the data to realistic loading, full-size prototypes and imperfect structures add much more complexity to the assessment of damage and they highlight the importance of expert opinion in dealing with the complexity [12].

While linguistic information represents subjective knowledge, owners and stakeholders of buildings are not satisfied with existing subjectiveness, no matter its reasons. Due to its very special characteristics, fuzzy-logic allows the development of a calculation procedure, which is optimally adapted to the problem to be solved. When analyzing features of relevant data, it can manage high dimensional search spaces, which are too large for being captured with human eyes. Besides, capable of dealing with vague data, fuzzy-sets may quantify uncertainties of the cause-effect relationship of damage. Accordingly by using fuzzy logic, the fact that experts do not dispose of adequate results to accurately define it or that they are not sure about their opinion, does no more represent a problem [10].

3.4 CHARACTERISTICS OF THE PROPOSED SYSTEM

In order to apply the criteria effectively, there is a need to limit the scope. The scope of undertaken work concerned with development of an expert system for assessing the damage states of reinforced concrete buildings in Gaza Strip. The proposed system was based on close visual inspections and simple measurements that do not require special testing or long-term investigation. Its prototype was developed considering the assessment activities performed at the building site and the office work, with a special emphasis on rationalizing procedures. The inputs are mostly linguistic variables concerning the state assessment of the building and some numeric data about concrete and environmental conditions.

As basic for the inputs, visual inspection has the following advantages [28]

1. It is the most effective qualitative method of evaluation of structural soundness and identifying the distress symptoms together with the associated problems.
2. It provides valuable information to an engineer in regard to structural serviceability and material deterioration mechanism.
3. It is meant to give a quick scan of the structure to assess its state.
4. The record of visual inspection is an essential requirement for preparation of realistic bill of quantities of various repair items.
5. It forms the basis for detailing out the plan of action to complete the diagnosis of problems and to quantify the extent of distress.

3.4.1 Features

In general, for expert system a heuristic component can operate on or use knowledge to make recommendations, draw conclusions, and/or propose a hypothesis. As heuristic software tool, the proposed damage assessment expert system has the following features:

- Number of valuable expertise regarding the damage cause and damage propagation of reinforced concrete buildings can be acquired through a considerable number of interviews.
- It is possible to deal with the uncertainty involved in data and knowledge by fuzzy logic.
- The fuzzy logic has also good applicability in subjective decision making problems.
- In order to improve the efficiency, it uses heuristics in damage assessment domain.
- In case of knowledge base updates it is conducive to change.
- The system has the advantage of enhancing the efficiency and reliability of assessment and flexibility concerning missing or inadequate criteria.

3.4.2 Knowledge Acquisition

Knowledge acquisition is a crucial aspect of developing a knowledge base and it is important that the source of knowledge for any system be carefully selected. The knowledge bases are developed using what are considered to be best sources available during the development stage. Because of the vast amount of knowledge and the need to assess its validity, acquiring and validating the knowledge is crucial and difficult.

For this purpose, the use of multiple sources is considered in developing the knowledge bases. In addition to extracting knowledge from experienced concrete specialists, it has been obtained from literature, codes of practice, manuals, textbooks, technical reports, journals and conference proceedings, and civil work reports. Most of the knowledge is directly taken from the following major organizations:

- American Concrete Institute
  - Building code requirements for structural concrete and commentary ACI 318.
  - Guide for making a condition survey of concrete in service, ACI 201.1R-92.
  - Guide for evaluation of concrete structures prior to rehabilitation, ACI 364.1R-94
  - Strength Evaluation of Existing Concrete Buildings, ACI 473 R-03
- British Standard.
- Uniform Building Code.
- European Standard.
  - EUROCODE2: Design of concrete structures
  - EUROCODE7: Geotechnical design
  - European Norm standards (EN1504),
- European projects manuals as: CONTECVET, NORECON, REHABCON, BRIME
- International Organization for Standardization (ISO),

3.4.3 Knowledge Domain

The ability of an expert system to solve a problem has been observed to increase with the extent of its domain knowledge. The most demanding phase of developing an expert system is obtaining and representing relevant knowledge. The knowledge contained in the proposed system includes information and rules on the criteria affecting the state assessment of the building such as; building history and construction condition, environmental condition, structural capacity and durability aspects. The knowledge domain and target user for the expert systems are illustrated in Figure 3.4.

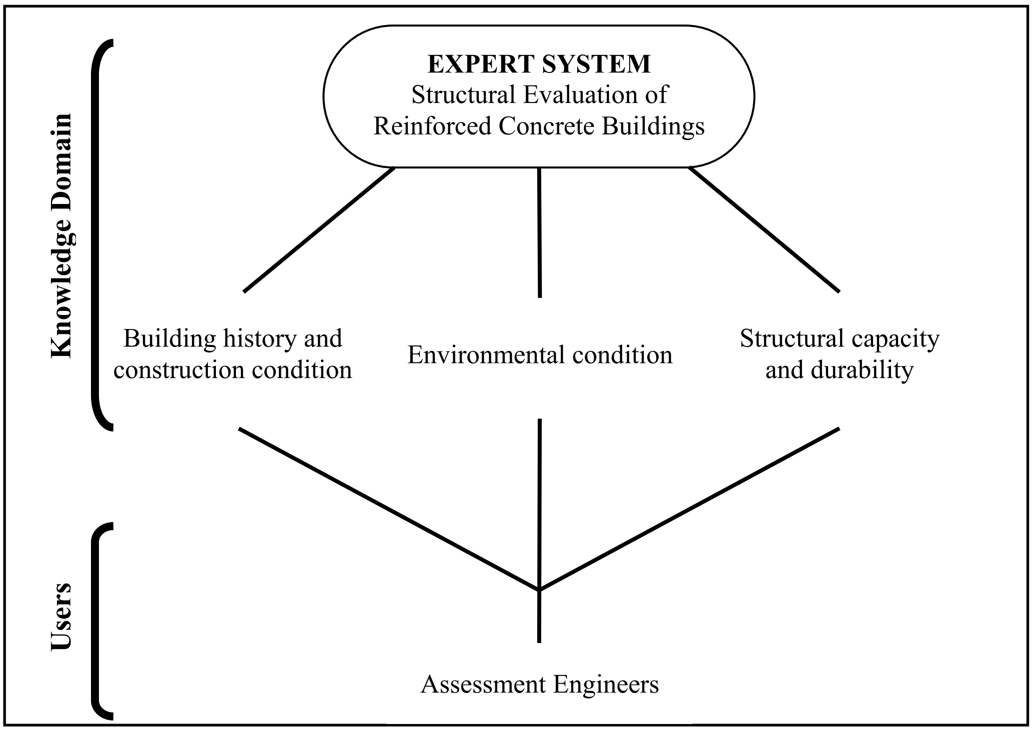

Figure 3.4: Knowledge domain and users.

3.4.4 Formalization of Assessment Criteria

The process of quantitative formalization of assessment criteria is essential in the state assessment. Quantifying subjective knowledge, which represents linguistic information using traditional mathematics, is usually impossible. However, fuzzy sets are commonly used for handling uncertainties associated with linguistic concept. It was introduced in quantizing criteria, which are difficult to represent quantitatively or fall short of clear judgment. The attributes of selected assessment criteria were formalized quantitatively with reference to building codes, former research, and building materials properties.

The number of possible conditions states is selected based on the degree of refinement in the distinction between states that the user is prepared to make. The linguistic variables were divided into five possible states (categories): very good (no damage), good (slight damage), moderate, bad (severe damage), and very bad (very extensive damage).

3.4.5 Development steps

The problem to be solved by expert system is to determine the sate condition of reinforced concrete building in Gaza strip. The system designed and developed depending on the experience and expertise of experts. The procedures for developing the proposed System are divided into main two steps; designing and implementation. For each there are list of procedures as shown in Figure 3.5 as follow:

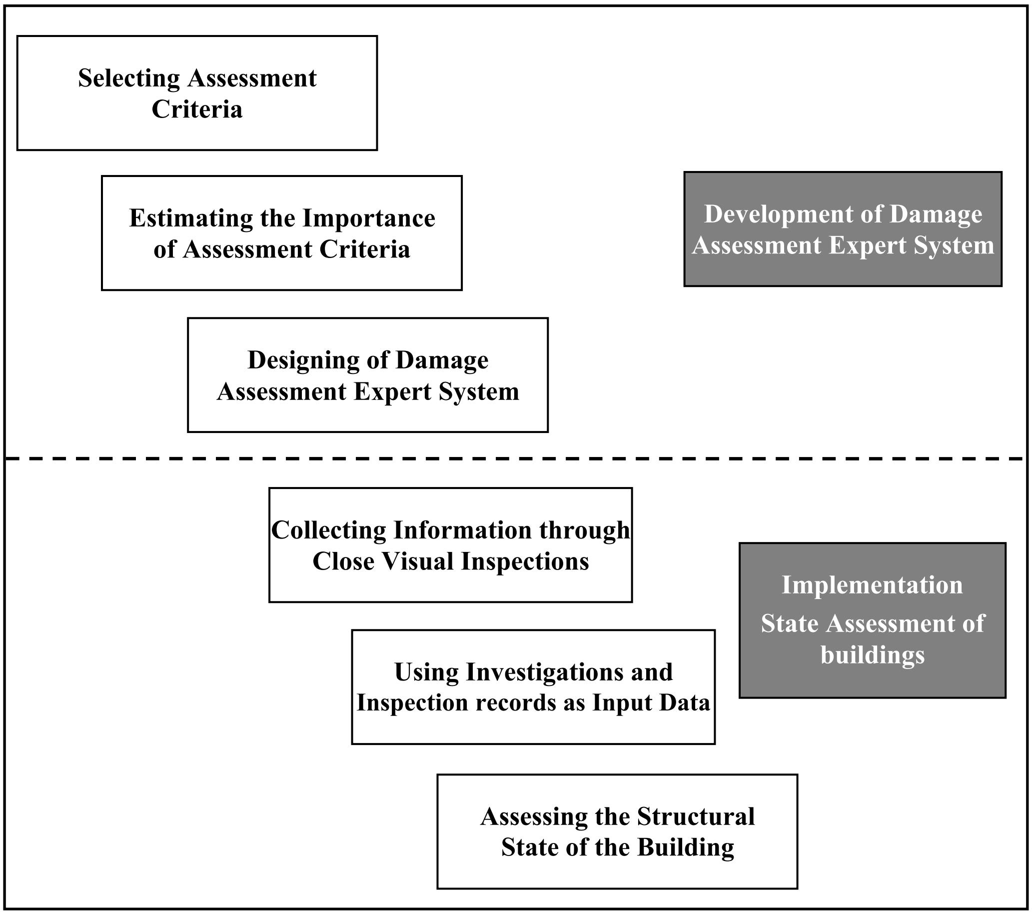

Figure 3.5: Scheme of damage assessment expert system

a) Designing

Selecting Assessment Criteria; the structural evaluation of a building involves several criteria that should be considered. When determining the structural condition of the building the first step is to select the criteria that will indicate the structural condition. The criteria will be selected based on inspection results and the previous records of regular inspections. They will be such basic items that can be inspected by close visual inspections and do not require special testing or long-term investigation.

Estimating the Importance of Assessment Criteria; this step depends on the experience and expertise of experts, particularly in a subjective assessment domain. In the evaluation of any structure, decisions must be made on the weighting to be given to the different observations and calculations relating to the strength and serviceability of individual members and to their effect on the overall structure.

Designing of Damage Assessment Expert System; the third step will be development an expert system for condition evaluation that includes final state assessment of the building and recommended action. In this expert system, fuzzy sets used as knowledge representation tool.

b) Application

Although there is a claim that every building is unique, many similar characteristics of structures should allow the development of type-specific condition assessment. In particular, the following steps are applied to assess the damage state of the building.

Investigating and inspecting; collection and evaluation of information through close visual inspection, document search, on-site non-destructive examination and available past records to establish the present condition of the building

Input Data; investigation and inspection records of the previous step used as input data of the expert system.

Assessing the Structural State of the Building; the last step is to state assessment of the building under consideration

CHAPTER FOUR:
STRUCTURAL ASSESSMENT CRITERIA

4.1 INTRODUCTION

To select structural assessment criteria for evaluation of reinforced concrete buildings in Gaza strip, it is significant to understand the nature of the buildings. Previous researches have shown that the reinforced concrete construction systems used in Gaza Strip fall within two main systems, the reinforced concrete with concrete block bearing walls system, and the reinforced concrete skeleton system. Reinforced concrete buildings in Gaza Strip had appeared in the beginning of 1950's or earlier. Buildings in this period comprised thin two-way solid slabs with drop beams or steel I-beams supported on concrete blocks bearing walls or on drop beams resting on concrete block walls. The concrete was made of coarse and fine aggregates and cement. The sand was mainly seashore sand. Reinforcing steel bars used were of the round mild steel. Buildings constructed in the late of 1970's and the beginning of 1980's, were reinforced concrete skeleton system that used one-way or two-way slabs on drop or hidden beams supported on columns which transform the loads to foundations. Shear walls or moment resisting frames were used to resist lateral forces especially in high-rise buildings. The slabs were solid, ribbed, or sometimes waffle slabs, while columns were rectangular or with circular cross-section, and foundations were of various types such as single, combined, raft, etc. Deformed steel bars were the main reinforcement in concrete structural members while concrete hollow blocks were used in these buildings as external and internal walls [8].

This study essentially adopted structural criteria for assessment. Meanwhile there are several factors affecting the decision for retrofitting and strengthening a building. Despite it is structurally safe and can sustain the applied loads, sometimes it is economically to remove the building rather than to strengthening it. Nuti and Vanzi [29] proposed a simple procedure to make a decision whether it is economically pertinent to retrofit a structure or not. Historic value of the building is another constraint in assessment process. These buildings are regional cultural assets that worth preserving. However, old buildings, which were designed by codes that are now known to provide inadequate safety, are likely to be vulnerable to severe damage or collapse. Such contemporary code requirements and engineering knowledge base were not available to designers and builders at the time historic buildings were typically designed and constructed. In particular cases, social impacts on the residents of the assessed building and sociality of assessment engineer also affect the decisions, where some people get afraid and do not trust the retrofitted building and prefer a new one.

4.2 SELECTING ASSESSMENT CRITERIA

The structural evaluation of a building involves several criteria that should be considered. In this study, the criteria were selected based on inspection results and the previous records of regular inspections. As stated earlier, the adopted criteria can be inspected by close visual inspections and simple measurements, which do not require special testing or long-term investigation. They were classified hierarchically according to assessment divisions so that systematic analysis and manipulation could be carried out.

The categories considered in the assessment include the state of building history, environmental conditions, structural capacity, durability, and professional involvement. These five main criteria include levels of sub-criteria. Figure 4.1 shows the hierarchical structure of the main criteria and the assessment sub criteria. The objective at the goal level is to determine the overall structural state assessment of a building, while at the first level; the hierarchic structure is separated into five main criteria.

The concept adopted here is to divide the problem of evaluation the structural state of the building, into a level of simpler problems, which, in turn are subdivided into even simpler problems at corresponding lower levels. The number of levels used in the solution of a problem will depend on the complexity of the problem. This process is repeated until a level is reached in which the problems or questions posed can be answered by the user (engineer) based on either his expertise or on an observed or computed value.

The inputs to the system are mostly linguistic variables and some numeric data concerning the selected categories for the assigned criterion. They extracted from the reports of the buildings assessment. The state conditions for criteria were constructed by extracting knowledge from technical books and experts in the domain field. The following sections describe the selected assessment criteria in more details.

4.2.1 Building History State (BH)

The history state of a building can be acquired by previous reports and documents. It is used to describe change shape and usage of the building through its life span and consequently alteration of structural member. During the life span of the building, it is expected to be exposed to variety of accidents; (earthquakes, fires, explosions, flood damage, and or impact, etc.). As sub criteria of building history state, the shape and usage changes of a building, alteration of structural members, the accident history, and the service years, are categorized. Though they may not have caused direct damage, it is probable that such incidents weaken the structure’s stiffness or strength for a long or short-term duration. It serves as indirect assessment criteria [3, 4].

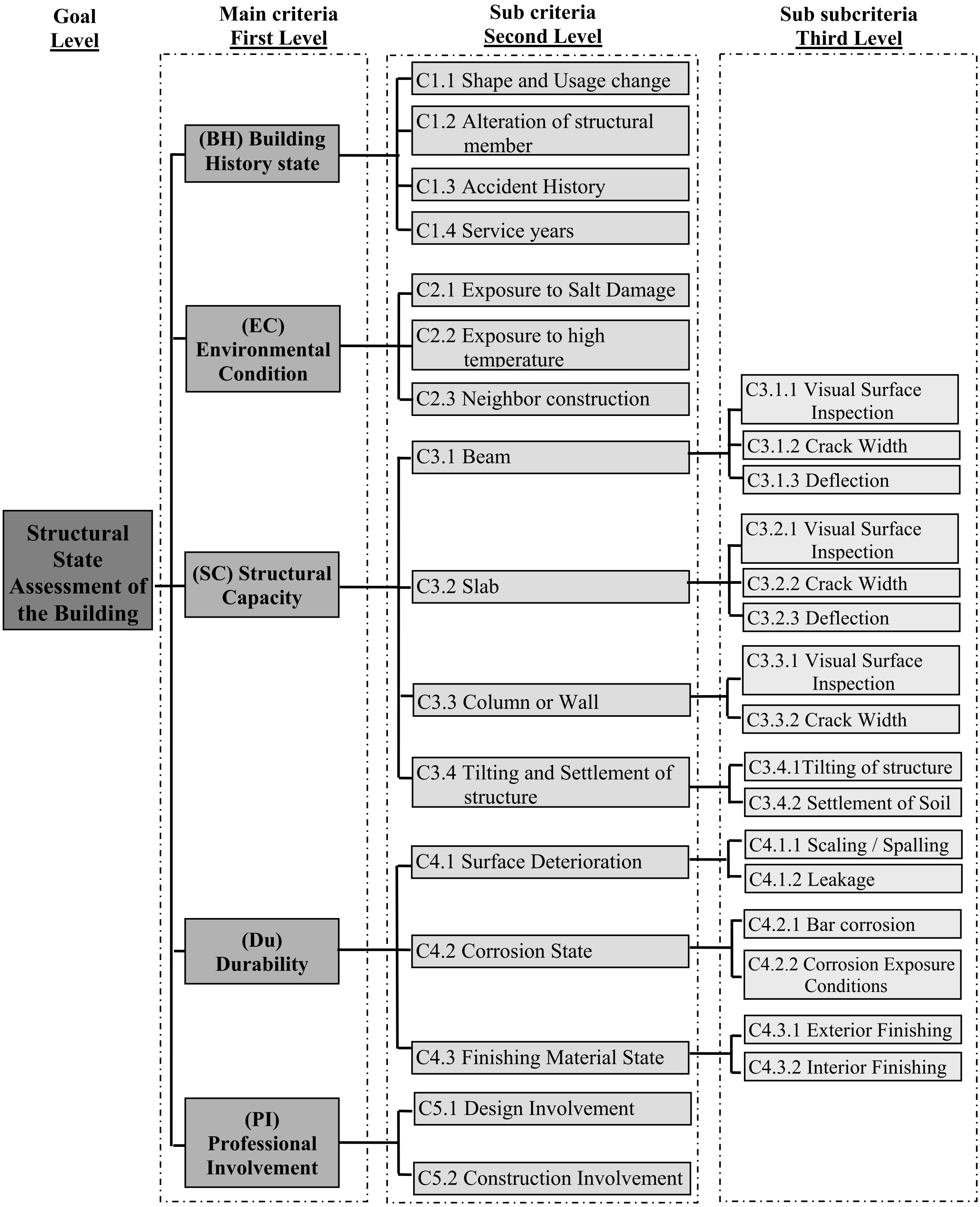

Figure 4.1: The hierarchy of assessment criteria

4.2.1.1 Fuzzy Evaluation of Building History Sub-criteria

The factors selected for assessing building history state are evaluated by their quality, and they are the lowest level in this criterion. Each of these factors has categories that can be answered by the user to establish the degree of membership for the states that correspond to the five defined states. Table 4.1 shows the possible state condition of each sub criterion for building history state.

Table 4.1:
State conditions for Building History state

Sub-criterion	Linguistic variable	State condition
C1.1; Shape and usage change.	Very good	No change of shape and/or usage.
	Good	Partial change of shape and/or usage with slight increase of load.
	Moderate	Overall change of shape and/or usage with slight increase of load.
	Bad	Partial change of shape and/or usage with large increase of load.
	Very bad	Overall change of shape and/or usage with large increase of load.
C1.2; Alteration of structural members.	Very good	No alteration of structural members.
	Good	Partial alteration of structural members with slight effect.
	Moderate	Moderate effect due to alteration of structural member.
	Bad	Severe effect due to alteration of structural member.
	Very bad	Overall alteration of structural members with extensive effect.
C1.3; Accident history.	Very good	No records for accident history.
	Good	Records of accident with slight structural effects.
	Moderate	Records of accident with moderate structural effect.
	Bad	Records of repeated accident with bad structural effects.
	Very bad	Records of repeated accident with extensive structural effect.
C1.4 service years	Very good	Lifespan is less than 10 years.
	Good	Lifespan ranges from 10 to 30 years.
	Moderate	Lifespan ranges from 30 to 50 years.
	Bad	Lifespan ranges from 50 to 70 years.
	Very bad	Lifespan is more than 70 years.

Obviously, choosing a specific category involves considerable judgement since the boundaries between categories are not defined precisely and there is likelihood that a different investigator or the same investigator at a different point in time may select another category. Because only one category can be selected, this vagueness is represented by assigning degrees of membership to the different states in the goal sub-set. Table 4.2 shows the degrees of membership for the category selected which are assigned to the sub criteria in building history state. For illustration, the selection of category VG shows strong support for goal sub-set state v_1 moderate support for v_2 and v_3, little support for v_3 and no support for v_4 and v_5. Similarly, selecting a different category does not preclude support for adjacent states in goal sub-set.

Table 4.2:
Degrees of membership for building history state

Categories for building history state		v_1	v_2	v_3	v_4	v_5
VG	Very good	1.0	0.5	0.2	0.0	0.0
G	Good	0.5	1.0	0.5	0.0	0.0
M	Moderate	0.1	0.5	1.0	0.5	0.1
B	Bad	0.0	0.0	0.5	1.0	0.5
VB	Very bad	0.0	0.0	0.2	0.5	1.0

4.2.2 Environmental Conditions (EC)

Largely the environment and the quality of concrete affect deterioration of concrete structure and the rate of degradation. The environmental condition could be the surrounding; temperature, humidity, chemicals, etc., of a structure or structural member to which it is exposed to in addition to the mechanical actions,. It may be caused by natural or artificial circumstances with which buildings are faced, and thus it includes; 1) exposure to salt damage, 2) exposure to high temperature or vibration, and 3) the neighbor construction state [28, 30].

4.2.2.1 Exposure to Salt Damages

Salts leach through the surface of concrete and appear as efflorescence. Efflorescence occurs quite frequently on the surface of concrete when water can percolate through the material continuously or intermittently, or when an exposed face alternately wetted and dried. It consists of deposited salts that are leached out of the concrete and are crystallized on subsequent evaporation of the water or interaction with carbon dioxide in the atmosphere. In itself, efflorescence is an aesthetic rather than a durability problem, but it does indicate that substantial leaching is occurring within the concrete. However, extensive leaching causes an increase in porosity, and lowering the strength of concrete. Concrete is not significantly leached by water flowing over its surface unless accompanied by physical abrasion [31].

4.2.2.2 Exposure to High Temperatures

It can be concluded that within the normal environmental temperature range, the thermal properties of concrete can be considered constant, if there is no change in moisture content. At elevated temperatures, these properties change due to changes in the moisture content of the concrete and progressive deterioration of the paste and in some cases of the aggregate. These processes depend on the conditions of the exposure, which include: the rate of temperature rise, the maximum temperature, and the time at elevated temperatures. Mindess and Young [31] indicated that the strength of concrete at elevated temperatures is usually maintained up to about 300ºC, unless large temperature differentials are allowed to develop (rapid heating), whereas above this temperature significant decreases can be anticipated.

The extent of damage due to high temperature depends on the temperature reached, loading conditions under fire, and characteristics of the concrete. The effect of high temperatures will change the properties of concrete this will be noticed by eyes. Up to 300 º C, the concrete maintain its normal color. For temperatures from about 300ºC to 600ºC, concrete color changes to pink or red. For temperatures from about 600ºC to 1000ºC, concrete color changes gray. However, for temperatures greater than about 1000ºC the concrete color change to buff color [31].

4.2.2.3 Neighbor Constructions

Many reinforced concrete buildings in Gaza strip were damaged because of Israeli army attacks that caused total or partial collapse. In general, buildings in Gaza strip are very close or even attached. This situation makes the neighborhood building affected as well as the targeted building. These effects depend on; volume of explosion, repetition of bombing and the distance between buildings.

4.2.2.4 Fuzzy Evaluation of Environmental Conditions Sub-criteria

When evaluating environmental conditions sub criteria, it should be taken into consideration that they are physical observations and have linguistic variables, which their state are quality evaluated. The lowest level in this criterion are; exposure to salt damage, exposure to high temperature or vibration, and the neighbor construction state. The user in the lowest level will choose one of five categories. The possible state conditions of these categories are listed in Table 4.3. The vagueness in selection one category among the others is also handled using fuzzy sets and the degrees of membership values are listed in Table 4.4.

Table 4.3:
State conditions for environmental condition sub-criteria

Sub-criterion	Linguistic variable	State condition
C2.1; Exposure to salt damage.	Very good	No exposure to salt damage.
	Good	Small concentrations of salt in the atmosphere, away from seacoast)
	Moderate	Moderate connotation of salts (relatively close to the coast).
	Bad	Exposed to large amount of salts in atmosphere (close to the coast with sewage and water pipes problems).
	Very bad	Exposed to severe attack by salts and appearance of efflorescence.
C2.2; exposure to high temperature.	Very good	Exposed to natural temperature, atmospheric temperature
	Good	Exposed to high temperature above normal but less than 300ºC (normal concrete color).
	Moderate	Exposed temperature ranges from 300 to 600ºC (pink or red color).
	Bad	Exposed temperature ranges from 600 to 1000ºC (Gray color).
	Very bad	Exposed to temperature more than 1000ºC (buff color).
C2.3; neighbor constructions	Very good	No neighbor constructions
	Good	Neighbor constructions exposed to damage with no effects.
	Moderate	Neighbor constructions exposed to a bombing with slight effect.
	Bad	Neighbor constructions exposed to bombings with massive effects.
	Very bad	Severe structural effects due to neighbor constructions.

Table 4.4:
Degrees of membership for environmental conditions.

Categories for environmental conditions		v_1	v_2	v_3	v_4	v_5
VG	Very good	1.0	0.6	0.2	0.0	0.0
G	Good	0.6	1.0	0.6	0.1	0.0
M	Moderate	0.0	0.6	1.0	0.6	0.0
B	Bad	0.0	0.1	0.6	1.0	0.6
VB	Very bad	0.0	0.0	0.2	0.6	1.0

4.2.3 Structural Capacity (SC)

Strength or structural capacity is the ability of a structure or structural members to resist external force. It can be expressed as the ratio of the provided capacity of the member to the required capacity. One objective of the assessment is to verify that the load carrying capacity of the cross sections is greater than the load effects originating from the loading. The structural capacity of the existing reinforced concrete buildings can be assessed through strength evaluation of its structural member including; load testing and ascertain whether a part or all of a structure meets the capacity required by the design code. This criterion assesses all structural members of the evaluated building including horizontal and vertical member (beams slabs and columns and/or walls), in addition to overall tilting and settlement of the structure. For each of which the current condition must be inferred from an evaluation of each individual member. To arrive at the goal sub-set representing the condition of a structural member, it is necessary to combine these factors taking into account their relative importance. Unless there is some reason for weighting the beams, slabs and columns /walls differently, all members are assumed to have the same influence on the overall condition of the structure.

Experience indicates that if there are no signs of distress in a member of an existing structure then there is little reason to undertake a full evaluation of the strength for that member. However, these direct measurements and tests are beyond the scope of this research. As third level sub criteria for beam and slab; Visual Surface Inspection, Crack Width, and Deflection are chosen, while for columns; Visual Surface Inspection and Crack Width. It represent the lowest level in the system that user engineer can evaluate [4, 28].

4.2.3.1 Visual Surface Inspection

Visual surface inspection of a structure is the most effective qualitative method of evaluation of structural soundness and identifying the typical distress symptoms together with the associated problems. It provides valuable information to an engineer concerning its workmanship, structural serviceability and material deterioration mechanism. It is meant to give a quick scan of the structure to assess its state of general health. At the same time, it is necessary that the engineer conducting visual inspection should have necessary familiarity with its structural system, structural behavior and serviceability requirements [32].

4.2.3.2 Crack Width

Crack width is important criterions that can be clearly assess the structural capacity of a member without any need for deep testing and investigations. Investigator engineer may approximate it. However, for accuracy crack width can be measured using crack microscope of various accuracies (e.g. 0.01 mm). The requirement of design codes places crack width in serviceability limit states. By EUROCOD 2, the recommended values for limiting calculated crack width for reinforced members range between 0.4 mm and 0.3 mm depending on exposure classes [32]. However according to American

Concrete Institute (ACI 318 – 05), Crack widths in structures are highly variable. In codes before the 1999 edition, a calculated maximum crack width of 0.4 mm is used [33]. Meanwhile British Standard BS8110 indicates that in normal internal or external conditions of exposure the assessed surface width of cracks should not exceed 0.3 mm for appearance and corrosion [34].

4.2.3.3 Deflection

The serviceability limit states for deflection will be met by complying with the span/effective depth ratios provided by design codes. The general requirement for deflection is that neither the efficiency nor the appearance of a structure is harmed by the deflections that will occur during its life. For structural members that are visible, the final deflection (including the effects of creep, shrinkage and temperature) measured below the as-cast level of the supports of horizontal members should not in general, exceed (L)span/250, where if the deflection exceeds this limit the sag in a member will usually become noticeable. This limit state is also adopted in EUROCODE 2. In practical, deflection can be measured as the distance below a horizontal line joining the level of the supports [32, 34, 35].

4.2.3.4 Tilting and Settlement

Tilting of structure caused due lateral stresses or it may be due to differential settlement of foundation. Tilting of structure can be represented by story drift, which is the displacement of one level relative to the level above or below. In the provisions of Unified Building Code, UBC94, the story drift (out-of-alignment) shall not exceed 0.005 times the story height (h_s) for building with structural fundamental periods <0.70 seconds and 0.004 for period $\geq$ 7 seconds. This limit may be exceeded when it is demonstrated that greater drift can be tolerated by both structural elements and nonstructural elements that could affect life safety [36].

Settlement of soil under building foundation can be estimated from a field survey of the building. Cracks in concrete elements are believed to be an indicator for settlement. As per EUROCODE 7, total settlements up to 50 mm are often acceptable for normal structures with isolated foundations. Larger settlements may be acceptable provided the relative rotations remain within acceptable limits and the total settlements do not cause problems with the services entering the structure, or cause tilting [37].

4.2.3.5 Fuzzy Evaluation of Structural Capacity Sub-criteria

The input to lowest level of these sub criteria may be linguistic or computed value. The user engineer will choose one of five categories or enter the computed value to the system, and this value refers to predefined category. The possible state conditions of these categories are listed in Table 4.5.

However, experience indicates that if there are no signs of deterioration in a member of an existing structure then there is little reason to undertake a full investigation of crack width and deflection or story drift for that member. In other words for any structural member, if it was seen that there are no noticeable deterioration, then there is no reason to investigate the crack width and deflection or story drift for that member. This is considered by the proposed system using rules. Let visual surface inspection, crack width, deflection and story drift are denoted by VSI, CW, def. and SD respectively, the following are the rules invoked.

– IF {(VSI=VG)} Then {(CW=VG) and (def. = VG) or (SD = VG)}

Consequently, a degree of membership of 1.0 is assigned to state v_1 and 0.0 to others.

– IF {(VSI=VB)} Then {(CW=VB) and (def. = VB) or (SD = VB)}

Consequently, a degree of membership of 1.0 is assigned to state v_5 and 0.0 to others.

Table 4.5:
State conditions for structural capacity sub-criteria

Sub-criterion	**Linguistic variable**	**State condition**
C3.1; Visual surface inspection.	Very good	No surface deterioration,
	Good	Visible shrinkage cracking only, micro cracks.
	Moderate	Moderate deterioration with possible deformation and cracks
	Bad	Bad deterioration (crack extended into the concrete member), crushed concrete, and/or deformation of concrete surface
	Very bad	Severe deterioration, crushing large amount of concrete
C3.2; Crack width	Very good	Hair cracks, Maximum crack width less than 0.4 mm
	Good	Very small cracks, Maximum crack width ranges from 0.4 to 0.8 mm
	Moderate	Visible cracks, Maximum crack width ranges from 0.6 to 1.0 mm
	Bad	Large cracks, Maximum crack width ranges from 0.8 to 1.2 mm
	Very bad	Very large cracks, Maximum crack width greater than 1.2 mm
C2.3; Deflection	Very good	No noticeable deflection, Maximum deflection less than L/250
	Good	Light deflection, Maximum deflection ranges from L/240 to L/210
	Moderate	Maximum deflection ranges from L/200 to L/180
	Bad	Maximum deflection ranges from L/170 to L/160
	Very bad	Severe deflection, Maximum deflection greater L/150
C3.4.1; Tilting of structure	Very good	No noticeable tilting, Story drift is less than 0.004 h_s
	Good	story drift ranges from 0.005 h_s to 0.007 h_s
	Moderate	Moderate tilting, story drift ranges from 0.008 h_s to 0.010 h_s
	Bad	story drift ranges from 0.010 h_s to 0.012 h_s
	Very bad	Severe tilting, story drift is greater than 0.012 h_s
C3.4.1; settlement of soil	Very good	No observed settlement.
	Good	Cracks in nonstructural elements (approximate settlement ≤50 mm)
	Moderate	Observed cracks in nonstructural and, slight cracks of structural elements related to foundation settlements
	Bad	Heavy cracks in structural elements related to foundation settlement
	Very bad	Severe cracks, approximate settlement ≥ 1000mm

As shown in Table 4.5, the boundaries between categories of visual surface inspection are not precisely defined and there is likelihood that a different investigator or the same investigator at a different point in time may select another category. This vagueness is assigned by degrees of membership to the different states as listed in Table 4.6.

The issue is different for crack width, it is a measured quantity that can be recorded or approximated, but its effect on the overall condition of any member is a fuzzy, thereby its degrees of membership to the different states must be assigned. This is done internally in the designed expert system using the ranges shown in Figure 4.2. As in the figure, the serviceability limit state of 0.4 mm crack width was adopted based on ACI [33] and chosen to be the transition point from v_1 to v_2 and the transition to v_5 of 1.2 mm corresponds to the limit for dangerous state as experience indicates. The other points are proportioned between these two transition points. For example, a crack width of 0.4 or less would assign a degree of membership supporting state v_1 of 1.0 and 0.0 for the other states whereas a maximum crack width of 0.50 would be interpreted as having degrees of membership supporting states v_1 and v_2 of 0.5 and 0.0 for other states. In a similar manner, the deflections for horizontal members can be a measured quantity that directly inputted by investigator and the system assigns degrees of membership in relation to the level of support for the different states as shown in Figure 4.3.

Table 4.6:
Degrees of membership for visual surface inspection

Categories for Visual surface inspection		v_1	v_2	v_3	v_4	v_5
VG	Very good	1.0	0.6	0.3	0.0	0.0
G	Good	0.6	1.0	0.6	0.0	0.0
M	Moderate	0.1	0.6	1.0	0.6	0.1
B	Bad	0.0	0.0	0.6	1.0	0.6
VB	Very bad	0.0	0.0	0.3	0.6	1.0

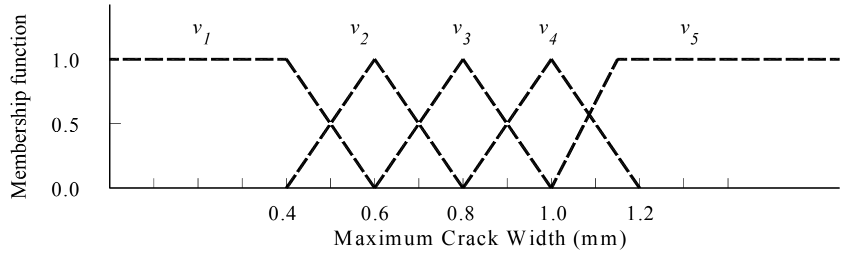

Figure 4.2 Membership function for maximum crack width

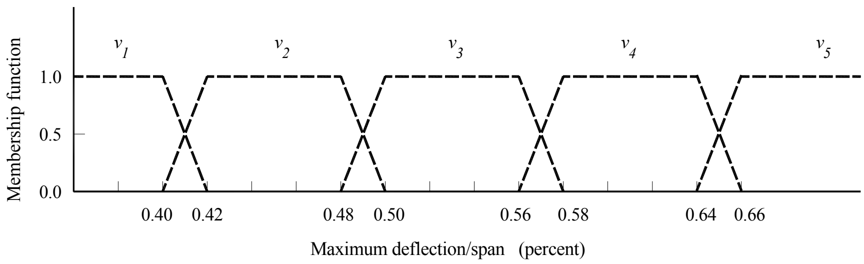

Figure 4.3: Membership function for deflection

Settlement of soil can not be easily defined. It has linguistic variables, which their states are quality evaluated. There is likelihood that a different investigator may select different category. The assigned degrees of membership to handle this vagueness are shown in Table 4.7. However, With regard to tilting of structure, the inputs are computed value for story drift. Its assigned degrees of memberships are in Figure 4.4.

Table 4.7:
Degrees of membership for settlement of soil

Categories for settlement of soil		v_1	v_2	v_3	v_4	v_5
VG	Very good	1.0	0.7	0.3	0.0	0.0
G	Good	0.7	1.0	0.7	0.1	0.0
M	Moderate	0.1	0.7	1	0.7	0.1
B	Bad	0.0	0.1	0.7	1.0	0.7
VB	Very bad	0.0	0.0	0.3	0.7	1.0

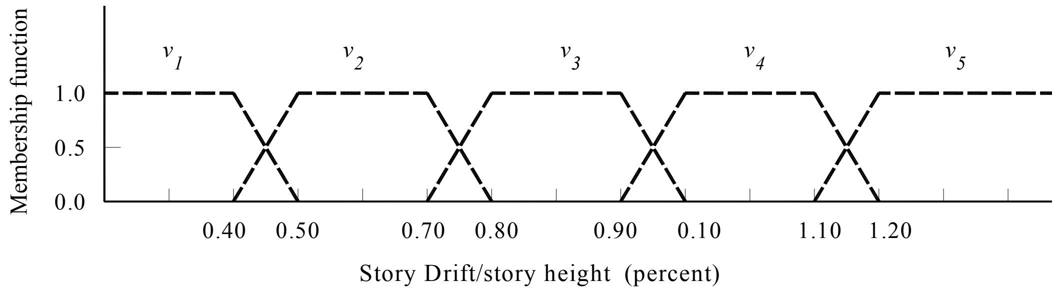

Figure 4.4: Membership function for story drift

4.2.4 Durability (Du)

Concrete is inherently a durable material. If properly designed for the environment to which it will be exposed and if carefully produced with good quality control, concrete is capable of maintenance- free performance for decades without the need for protective coatings, except in highly corrosive environment [31]. Based on BS8110 a durable concrete element is one that is designed and constructed to protect embedded metal from corrosion and to perform satisfactorily in the working environment for the life-time of the structure. Leave it to concrete alone, the material remains durable, but concrete alone can not be utilized extensively for structural applications [34]. Concrete is potentially vulnerable to attack in variety of different exposures unless certain precautions are taken. Deterioration of concrete can be due to either chemical or physical causes, where all concrete in service will be subject these causes. If the visible symptoms are observed on the surface, it can be assumed that the interior of the concrete is severely damaged. Thereby durability plays an important role in the assessment criteria of reinforced concrete structures in relation to structural capacity.

In this research, surface deterioration, corrosion state, and deterioration of finishing materials were selected as sub criteria for durability. Ignoring these conditions leads to the rapid decline of concrete durability and hence the decline of structural capacity.

4.2.4.1 Surface Deterioration

Surface deterioration divided into scaling and/or spalling and leakage. In the proposed system, scaling/ spalling should be assessed for each of the vertical members (column or wall) of the building and leakage for the horizontal members. Scaling is a local flaking or peeling away of the near-surface portion of hardened concrete or mortar. It may be; light scaling (loss of surface mortar without exposure of coarse aggregate), medium scaling (loss of surface mortar 5 to 10 mm and exposure of coarse aggregate), severe scaling (loss of surface mortar 5 to 10 mm with some loss of mortar surrounding aggregate particles 10 to 20 mm), and very severe scaling (loss of coarse aggregate particles as well as mortar, generally to a depth greater than 20 mm). However, Spalling is a deeper surface defect than scaling, often appearing as circular or oval depressions on surfaces or as elongated cavities along joints. Spalls may be 25mm or more in depth and 150 mm or more in diameter, although smaller spalls also occur [38].

Leakage effect is a function of permeability of concrete. As deterioration process begins with penetration of various aggressive agents, low permeability is the key to its durability, where, intermittent exposure to water (rain or wetting/drying cycle due to leakage) is the most favorable condition for corrosion of reinforcing steel. Leakage may not be noticeable to the eyes due to flooring tiles, but damage continues until spalling of cover concrete takes place. In assessment practice, wetting the concrete surface with water and monitoring the leakage is conducted as a simple test for permeability. Heavy leakage indicates of very bad condition of concrete members as well as other state conditions [28].

4.2.4.2 Corrosion State

Corrosion of reinforcement steel bars is the most frequent deterioration mechanism of reinforced concrete structures. As Gaza Strip is a coastal area, many buildings show signs of deterioration due to corrosion problem. In a good quality concrete, embedded reinforcing steel should not be liable to corrosion. This is because the high alkalinity presents within concrete that are produced by cement hydration, that give the pore solution of concrete a pH of around 13. This pH causes a passive oxide film to form on the surface and prevent corrosion as high pH is maintained and the cover concrete is intact even though oxygen and moisture may reach the steel surface. There are two common conditions that lead to destroy the passivating film: (1) Reduction alkalinity of concrete with pH lower than 11, (2) Presence of aggressive agents such as carbon dioxide (carbonation) or chloride ions even while the alkalinity of surrounding concrete remains high [31, 39].

For internal elements due to the lack of sufficient moisture, concrete remains durable even though carbonation can be substantial. For external elements, corrosion will occur once the concrete is carbonated close to the reinforcement. Thus, the quality and quantity (thickness) of the concrete cover play an important role in controlling the time to initiate corrosion. In normal practice, it may take 20 years or more to carbonate the cover. In a well cured concrete with low water to cement ratio (W/c<0.4), the depth of carbonated zone is unlikely to exceed 25 mm, thereby a concrete cover of 25 to 40 mm should provide adequate protection from corrosion [31].

The area where the concrete has lost bond with the reinforcing steel due to corrosion is called delamination area. It can be detected by tapping the concrete with a hammer, where a hollow sound indicates a delaminated area. The falling concrete due to delamination is of serious concern. It may pose as a safety hazard to pedestrians and vehicles traveling below deteriorated overpasses and buildings [28, 31].

4.2.4.3 Finishing Material State

The third sub criterion of durability is related to finishing material state. It is a qualitative measurement for the durability of the building. External or internal finishing material protects the structural ember from environmental aggressive agents. Its bad state refers to bad durability aspects. Damage of interior and exterior finishing material may be: falling, crack and/ or deformation of finishing material.

4.2.4.4 Fuzzy Evaluation of Durability Sub-criteria

Tables 4.8 shows possible state conditions of durability sub criteria, which are the inputs to the system by the user. From the table it is seen that scaling / spalling can be numeric value that entered to the system. Its assigned degrees of membership are listed in Figure 4.5. Whereas leakage is a qualitative value, and there is likelihood that a different investigator or the same investigator at a different point in time may select another category thereby choosing a specific category involves considerable judgement, thus the degrees of membership for leakage are as in Table 4.9.

For corrosion state also, choosing a category involves considerable judgement, where the sub criteria are a qualitative value and the boundaries between categories are not precisely defined. Table 4.10 includes the assigned degrees of membership that used to handle this vagueness.

In similar manner, finishing material state is a qualitative measurement and its state refers to quality of the building. Its assigned degrees of membership values are shown in Table 4.11.

Table 4.8:
State conditions for durability sub-criteria

Sub-criterion	Linguistic variable	State condition
C4.1.1; Scaling / Spalling.	Very good	No scaling / spalling.
	Good	Loss of surface mortar without exposure of coarse aggregate.
	Moderate	Loss of surface mortar with exposure of coarse aggregate (depth of surface mortar loss ranges from 5 to 10 mm).
	Bad	Loss of surface mortar with some loss of coarse aggregate (depth of surface mortar loss ranges from 10 to 20 mm).
	Very bad	Loss of coarse aggregate as well as surface mortar (depth of surface mortar loss is greater than 20 mm).
C4.1.2; Leakage	Very good	No observed leakage
	Good	Slight leakage in small area
	Moderate	Moderate leakage
	Bad	Bad leakage in big area
	Very bad	Very extensive leakage
C4.2.1; Bar corrosion	Very good	No observed corrosion.
	Good	Observed cracks with no delamination due to corrosion.
	Moderate	Sound test indicates moderate delamination
	Bad	Sound test indicates bad delamination.
	Very bad	Spalling delamination of concrete due to corrosion
C4.2.2; Corrosion exposure conditions	Very good	No exposure condition for corrosion
	Good	Slight corrosion conditions
	Moderate	Moderate corrosion conditions
	Bad	Bad conditions
	Very bad	Sever conditions
C4.3; Finishing material state	Very good	No damage
	Good	Partial slight damage
	Moderate	Overall slight damage
	Bad	Partial severe damage
	Very bad	Overall severe damage

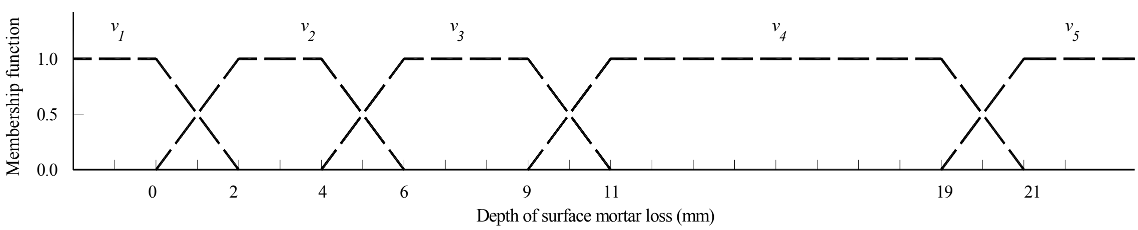

Figure 4.5: Membership function for scaling/spalling

Table 4.9:
Degrees of membership for leakage

Categories for leakage		v_1	v_2	v_3	v_4	v_5
VG	Very good	1.0	0.6	0.2	0.0	0.0
G	Good	0.6	1.0	0.6	0.1	0.0
M	Moderate	0.0	0.6	1.0	0.6	0.0
B	Bad	0.0	0.1	0.6	1.0	0.6
VB	Very bad	0.0	0.0	0.2	0.6	1.0

Table 4.10:
Degrees of membership for corrosion state

Categories for corrosion state		v_1	v_2	v_3	v_4	v_5
VG	Very good	1.0	0.5	0.1	0.0	0.0
G	Good	0.5	1.0	0.5	0.1	0.0
M	Moderate	0.1	0.5	1.0	0.5	0.1
B	Bad	0.0	0.1	0.5	1.0	0.5
VB	Very bad	0.0	0.0	0.1	0.5	1.0

Table 4.11:
Degrees of membership for finishing material state

Categories for finishing material state		v_1	v_2	v_3	v_4	v_5
VG	Very good	1.0	0.5	0.2	0.0	0.0
G	Good	0.5	1.0	0.5	0.0	0.0
M	Moderate	0.0	0.5	1.0	0.5	0.0
B	Bad	0.0	0.0	0.5	1.0	0.5
VB	Very bad	0.0	0.0	0.2	0.5	1.0

4.2.5 Professional Involvement (PI)

Professional involvement represents the state that, if the building was constructed under professionals engineers supervision in design stage and/or in execution (construction) stage. It has a great effect on the physical condition of a building. It plays as indirect measure of building state in structural assessment. Many of private building in Gaza strip, that have been appeared in the beginning of 1950's or earlier believed to be constructed without any professional involvement in design or construction. On other hand, public buildings, which had been constructed later, were believed to be full design and supervision involvement. Meanwhile previous survey conducted in 1997 on a number of housing units in West bank and Gaza Strip revealed that more than 80% of units found to be in good or very good condition had full professional intervention on both the design and supervision during the execution. In the meantime 57% of units found in medium to very bad condition had no professional involvement [40].

4.2.5.1 Fuzzy Evaluation of Professional Involvement Sub-criteria

The information about professional involvement is obtained from previous records. It is qualitative information can be extracted from previous documents of the building- if available-. The five categories for evaluating professional involvement are listed in Table 4.12, while the assigned degrees of membership values to handle vagueness are as in Table 4.13.

Table 4.12:
Degrees of membership for Professional Involvement

Sub-criterion	Linguistic variable	State condition
C5.1; Design involvement	Very good	Full engineering involvement in design including; soil investigation and full integration among engineering disciplines (architectural, civil, mechanical, electrical)
	Good	Engineering involvement with no detailed drawings.
	Moderate	Partial engineering involvement in design.
	Bad	Just architectural sketch drawing used as design drawings
	Very bad	No engineering involvement in design.
C5.2; Construction involvement	Very good	Full engineering involvement in the construction, including resident engineer for supervision and contractor engineer.
	Good	Full involvement of contractor engineer with partial involvement of supervision
	Moderate	Partial involvement of both contractor and supervision engineers.
	Bad	Partial involvement of contractor engineer.
	Very bad	Execution by labor without engineering involvement

Table 4.13:
Degrees of membership for Professional Involvement

Categories for Professional Involvement		v_1	v_2	v_3	v_4	v_5
VG	Very good	1.00	0.50	0.25	0.00	0.00
G	Good	0.50	1.00	0.50	0.00	0.00
M	Moderate	0.00	0.50	1.00	0.50	0.00
B	Bad	0.00	0.00	0.50	1.00	0.50
VB	Very bad	0.00	0.00	0.25	0.50	1.00

4.3 IMPORTANCE OF ASSESSMENT CRITERIA

4.3.1 Estimating The Weights of Assessment Criteria

Estimating the importance of assessment criteria is an important realm in itself, and depends heavily on the experience and expertise of experts, particularly in a subjective assessment domain. In the evaluation of any structure, decisions must be made on the weighting to be given to the different observations and calculations relating to the strength and serviceability of individual members and to their effect on the overall structure in other words to assessment criteria. State assessment is a kind of decision-making problem, and in particular a multi-criteria decision-making problem, wherein the criteria should satisfy multiple conditions. In this research, the weights of assessment criteria had been estimated using FAHP, which is discussed in section 2.3.8.

The general goal of this step is to estimate the local importance value or weight of the criterion, which satisfies $\sum_{i=1}^{n} w(x_i) = 1$ where n, is the number of the criteria in the specified level. The calculations of the processes in this step are according to the given hierarchy structure in section 4.2. After the criteria have been determined as given in Figure 4.1, a question form (questionnaire) has been prepared to determine the importance levels of these criteria. To evaluate the questions, experts only select the related linguistic variable, then for calculations, they are converted into a scale including triangular fuzzy numbers. Each linguistic variable has its own numerical value in the predefined scale. These numerical values are intervals between two numbers with most likely value. In the FAHP procedure, the pair-wise comparisons in the judgment matrix are fuzzy numbers that are modified by the designer's emphasis. To make a pair-wise comparison among the parameters in order to create a priority matrix, a relative importance scale has been developed. Figure 4.6 and Table 4.14 explain this scale, where in cases of inverse importance, the reciprocal of triangular fuzzy number scale is taken.

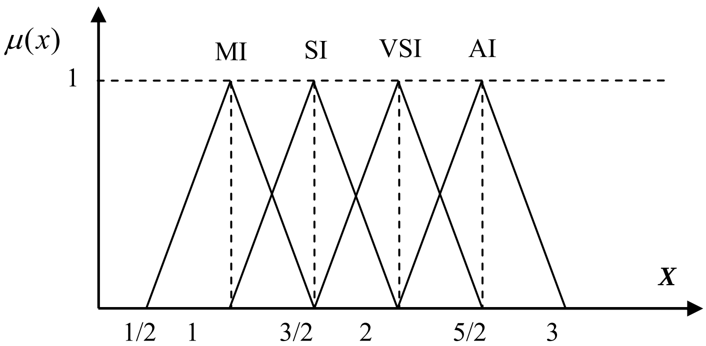

Figure 4.6: Triangular fuzzy importance scale

Table 4.14:
Triangular fuzzy numbers conversion scale

Linguistic scale for importance	Explanation	Triangular fuzzy scale	Triangular fuzzy Reciprocal scale
Equal importance (EI)	Two activities contribute equally to the objective	(1, 1, 1)	(1, 1, 1)
Moderate importance (MI)	Experience and judgment slightly favor one activity over another	(1/2, 1, 3/2)	(2/3, 1, 2)
Strong importance (SI)	Experience and judgment strongly favor one activity over another	(1, 3/2, 2)	(1/2, 2/3, 1)
Very strong importance (VSI)	An activity is favored very strongly over another;	(3/2, 2, 5/2)	(2/5, 1/2, 2/3)
Absolute importance (AI)	The evidence favoring one activity over another is the highest possible order of affirmation	(2, 5/2, 3)	(1/3, 2/5, 1/2)

The pair-wise comparison matrix is constructed by an individual interviews questionnaire survey of experts in the field of building assessment. Expert engineers who have been interviewed are involved in building assessment field and work essentially in the Ministry of Public Works and Housing and faculty of engineering in the Islamic University of Gaza. The questions are: "How much does the i^{th} criterion, compared to the j^{th} criterion, contribute in assessing the direct upper criteria (level) in a hierarchy of assessment criteria?" in other words how important is the i^{th} criterion when it is compared with j^{th} criterion with respect to upper level? With the possible answers, equal importance, moderate importance, strong importance, very strong importance, and absolute importance.

In appropriate with the FAHP method, main criteria have been selected and compared according to the goal level as well as the sub criteria, and then importance levels for each criterion have been found according to the given hierarchy structure. By starting with the first hierarchy level in Figure 4.1, which is separated into five main criteria; Building history state, Environmental conditions, structural capacity, durability, and Professional involvement. These criteria are compared with each other according to its upper level; "overall goal level (Structural State Assessment of the Building)" in order to importance the weights of these criteria. However to create the comparison matrix for this level, the following questions have been oriented to the expert:

Q1. How important is Building History when it is compared with Environmental Condition?
Q2. How important is Building History when it is compared with Structural Capacity?
Q3. How important is Building History when it is compared with Durability?
Q4. How important is Building History when it is compared with Professional Involvement?
Q5. How important is Environmental Condition when it is compared with Structural Capacity?
Q6. How important is Environmental Condition when it is compared with Durability?
Q7. How important is Environmental Condition when it is compared with Professional Involvement?
Q8. How important is Structural Capacity when it is compared with Durability?
Q9. How important is Structural Capacity when it is compared with Professional Involvement?
Q10. How important is Durability when it is compared with Professional Involvement?

The answers are put in a table such as Table 4.15. If a criterion on the left is more important than the one matching on the right, the answer check is marked to the left of the importance ''Equal'' under the preferred importance level. If a criterion on the left is less important than the one matching on the right, the check is marked to the right of the importance ''Equal'' under the preferred importance level.

Table 4.15:
Answers to main criteria interview questions

Questions	Criteria	Absolute (2,5/2,3)	Very strong (3/2, 2, 5/2)	Strong (1, 3/2, 2)	Moderate (1/2, 1, 3/2)	Equal (1, 1, 1)	Moderate (2/3, 1, 2)	Strong (1/2, 2/3, 1)	Very strong (2/5, 1/2, 2/3)	Absolute (1/3, 2/5, 1/2)	Criteria
Q1	B.H						√				E.C
Q2	B.H									√	S.C
Q3	B.H							√			Du.
Q4	B.H				√						P.I
Q5	E.C								√		S.C
Q6	E.C							√			Du.
Q7	E.C			√							P.I
Q8	S.C		√								Du.
Q9	S.C	√									P.I
Q10	Du.			√							P.I

According to the answers, the pairwise comparison matrix has been obtained as in Table 4.16 and the following steps are applied for the FAHP.

Table 4.16:
The fuzzy evaluation matrix with respect to the goal

	BH	**EC**	**SC**	**Du**	**PI**
BH	**(1,1,1)**	(2/3, 1, 2)	(1/3, 2/5,1/2)	(1/2, 2/3, 1)	(1/2, 1, 3/2)
EC	(1/2, 1, 3/2)	**(1,1,1)**	(2/5, 1/2,2/3)	(1/2, 2/3, 1)	(1, 3/2, 2)
SC	(2, 5/2, 3)	(3/2, 2, 5/2)	**(1,1,1)**	(3/2, 2, 5/2)	(2, 5/2, 3)
Du	(1, 3/2, 2)	(1, 3/2, 2)	(2/5, 1/2, 2/3)	**(1,1,1)**	(1, 3/2, 2)
PI	(2/3, 1, 2)	(1/2, 2/3, 1)	(1/3, 2/5, 1/2)	(1/2, 2/3, 1)	**(1,1,1)**

Step 1
From Table 4.16 and according to equation (2-6), the followings are calculated

	l	m	u
$\sum M_{B.H}$	3.00	4.07	6.00
$\sum M_{E.C}$	3.40	4.67	6.17
$\sum M_{S.C}$	8.00	10.00	12.00
$\sum M_{Du.}$	4.40	6.00	7.67
$\sum M_{PI}$	3.00	3.73	5.50

Using equation (2-7) ; $\sum_{i=1}^{n}\sum_{j=1}^{m} M_{gi}^{j} = (\sum_{i=1}^{n} l_i, \sum_{i=1}^{n} m_i, \sum_{i=1}^{n} u_i)$

	$\sum l_i$	$\sum m_i$	$\sum u_i$
$\sum\sum M_g$=	21.80	28.47	37.33

The inverse of the above vector is computed in equation. (2-8);

$$\left[\sum_{i=1}^{n}\sum_{j=1}^{m} M_{gi}^{j}\right]^{-1} = \left(\frac{1}{\sum_{i=1}^{n} u_i}, \frac{1}{\sum_{i=1}^{n} m_i}, \frac{1}{\sum_{i=1}^{n} l_i}\right)$$

$[\sum\sum M_g]^{-1}$	0.027	0.035	0.046

Then the synthesis values for each criterion are calculated by equation. (2-5).

$$S_i = \sum_{j=1}^{m} M_{gi}^{j} \otimes \left[\sum_{i=1}^{n}\sum_{j=1}^{m} M_{gi}^{j}\right]^{-1}$$

	L	m	u
S_{BH} =	0.08	0.14	0.28
S_{EC} =	0.09	0.16	0.28
S_{SC} =	0.21	0.35	0.55
S_{Du} =	0.12	0.21	0.35
S_{PI} =	0.08	0.13	0.25

Step 2

The obtained synthetic values are compared by using equation. (2-10);

$$V(M_2 \geq M_1) = \begin{cases} 1, & if, m_2 \geq m_1, \\ 0, & if, l_1 \geq u_2, \\ \dfrac{l_1 - u_2}{(m_2 - u_2) - (m_1 - l_1)}, & otherwise \quad , \end{cases}$$

and the following results are obtained:

$V(S_{BH}>S_{EC})$ =0.897	$V(S_{BH}>S_{SC})$ =0.226	$V(S_{BH}>S_{Du})$ =0.699	$V(S_{BH}>S_{PI})$ =1.000
$V(S_{EC}>S_{BH})$ =1.000	$V(S_{EC}>S_{SC})$ =0.268	$V(S_{EC}>S_{Du})$ =0.779	$V(S_{EC}>S_{PI})$ =1.000
$V(S_{SC}>S_{BH})$ =1.000	$V(S_{SC}>S_{EC})$ =1.000	$V(S_{SC}>S_{Du})$ =1.000	$V(S_{SC}>S_{PI})$ =1.000
$V(S_{Du}>S_{BH})$ =1.000	$V(S_{Du}>S_{EC})$ =1.000	$V(S_{Du}>S_{SC})$ =0.494	$V(S_{Du}>S_{PI})$ =1.000
$(V(S_{PI}>S_{BH})$ =0.936	$V(S_{PI}>S_{EC})$ =0.831	$V(S_{PI}>S_{SC})$ =0.147	$V(S_{PI}>S_{Du})$ =0.628

Step 3

The priority weights are calculated by using equation (2-12): $d'(A_i) = \min \; V(S_i \geq S_k)$

$d'(S_{BH})$ =0.226 $d'(S_{EC})$ = 0.268 $d'(S_{SC})$ = 1.000 $d'(S_{Du})$ = 0.494 $d'(S_{PI})$ =0.147

Step 4

The normalized weights vector with respect to the main criteria is obtained as:

Criterion	BH	EC	SC	Du	PI
W %	**10.6%**	**12.5%**	**46.8%**	**23.2%**	**6.9%**

Proceeding similar to the main criteria, second level and third level criteria have compared with respect to its upper level and then importance levels for each criterion have been calculated according to the given hierarchy structure. For each branch, each criteria group is subject to a pairwise comparison in itself. The criteria sets are calculated with the same approach and procedure is ended when importance levels are obtained. Figure 4.7 shows the obtained hierarchy of the proposed assessment criteria and its corresponding weights. The whole interview questions for all levels are included in Appendix A, while the matrices of pair-wise comparisons and the weight vector of each matrix for the second and third levels are given in Appendix B.

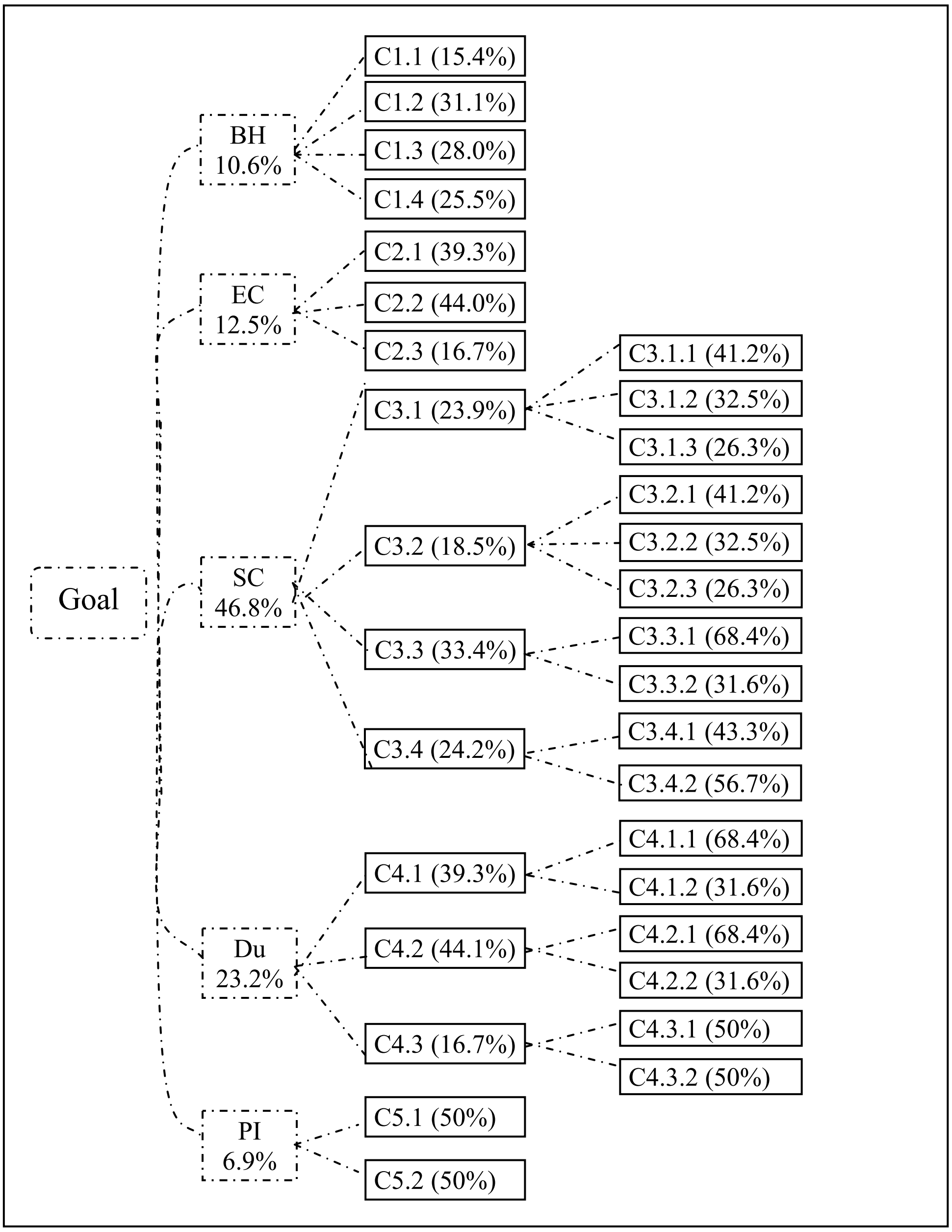

Figure 4.7: Weight factors of assessment criteria

4.3.2 Management of Missing Criteria

In many cases, missing or unavailable determinations of some criteria are a generally occurring problem in the area of decision-making or state assessment. To proceed with assessment considering missing criteria, the re-estimation of the importance of the available criteria is required. The effects of missing criteria depend on the contribution of these criteria to overall decision-making problem. Particularly in state assessment case, the effect of the missing criteria on the assessment depends on the degree of contribution of these missing criteria to the overall assessment and the relationship between these missing criteria and the available criteria. If all the assessment criteria act independently of each other, the existence of missing criteria means that the corresponding region cannot be assessed. On the other hand, if there is a redundancy among criteria, the region of missing criteria can be assessed to some extent according to the degree of redundancy. The missing criteria were managed by re-estimating the importance of the available criteria according to their redundancy, using the same procedure illustrated in previous sections, except that the missing criteria are not used in the estimation process.

For example, exposure to salt damage, exposure to high temperature and neighbor construction are three sub-criteria of environmental conditions with weights of 39.3%, 44% and 16.7 % respectively (refer to Figure4.7). If there exists unavailable information or inadequate data about exposure to high temperature sub-criterion, the weights of the other two sub-criteria will re-estimated in the same procedure previously illustrated and the re-estimated weights of exposure to salt damage, environmental conditions and neighbor construction will be 68.4%, 0.0% and 31.6% respectively.

CHAPTER FIVE:
DESIGNING THE STRUCTURAL EVALUATION EXPERT SYSTEM

5.1 OUTLINE OF THE SYSTEM

The expert system developed in this study performs modularized stepwise assessment according to the hierarchy of assessment categories and criteria. The main five categories in the determined hierarchy are; building history state, environmental conditions, structural capacity, durability, and professional involvement. They are the highest assessment criteria level. The evaluation of these five categories is processed from their detailed sub-criteria, and the evaluation of these detailed sub-criteria is also processed from more detailed sub-criteria in succession. This modularized stepwise assessment has the advantage of enhancing the efficiency and reliability of assessment process and flexibility concerning missing or inadequate criteria. The chosen criteria are quantized using fuzzy logic concepts. This has good applicability in subjective decision-making problems comprised of such quantized results and good possibilities for the proper assessment for missing or inadequate criteria.

5.2 MULTILEVEL HIERARCHY

The hierarchy multilevel is discussed in detail in chapter four. The concept adopted to construct the hierarchy is to divide the goal for solving the problem of evaluation the structural state of the building, into a five main criteria, which, in turn are subdivided into simpler criteria at corresponding lower levels. The number of levels used is three levels in addition to the goal level. This process was repeated until a level is reached in which the problems or questions posed can be answered by the user based on either his expertise or on an observed or computed value. These answers are expressed as fuzzy sets with appropriate membership values and are then combined using weighting factors and fuzzy composition. In this step-by-step way, answers are obtained for each successive level until the answer to the highest level or originally posed problem is obtained.

The final state of the assessed building was divided into five possible states or conditions (grades); very good, good, moderate, bad, and very bad. These five grades are the goal set of elements that represent the solution of the problem. Mathematically the goal set can be expressed as: $U = \{u_1, u_2, u_3, u_4, u_5\}$. Noting that U is a fuzzy set and so can have membership in any or all of the defined states, since it is the composition of many fuzzy sets used in the solution. For the designed system, the state with largest membership value is the most likely solution to the problem. In obtaining the goal set, at different level the state condition of criteria for such level has to be defined. This represents the sate of a sub-problem at that level. It can be referred as goal sub set and designated as *V* to distinguish it from a goal set *U*.

All criteria that are considered in the solution of the problem are expressed as fuzzy sets. Since the final goal set is obtained from these factors, all factor sets must have the five elements that are equal to the number of states in the goal set. For any factor set regardless of its condition, membership values are assigned to each of the factors considered. This will results in a matrix of membership values, which will have as many rows as the factors considered for the goal sub-set and five columns.

The importance of assessment criteria is of a great matter. In the evaluation of any structure, at any given level there will be several factor sets that contribute to the solution of the next higher-level. The number of elements in the weighting factor set must obviously correspond to the number of contributing factor sets. The weighting factor sets of assessment criteria at different level are discussed in chapter four. If missing criteria exist, these values should be re-estimated.

At the lowest level of the hierarchy, the inputs are linguistic variables and in some times numeric data concerning the selected categories for the assigned criterion. Concerning linguistic variable, the set is divided into five categories; very good, good, moderate, bad and very bad, from which the user selects. Associated with each input category there is a set of degrees of membership, which correspond to the level of support that category, has to the corresponding states in the goal set and sub set. It is convenient to normalize the membership values in a set, that is, to have the degrees of membership add to 1.0.

5.3 EVALUATING THE STRUCTURAL CONDITION OF A BUILDING

A possible strategy for evaluating the structural condition of a building is selected as described in Section 4.3 and Figure 4.1. The goal set is at the highest level, which contains the states that are to be used to define all possible conditions for the building. For the goal set "the structural evaluation of reinforced concrete buildings in Gaza Strip", five possible conditions states are adopted. Building structural states conditions and recommended actions are as shown in Table 5.1. The state of the assessed building is divided into five grades, those are; very good, good, moderate, bad, and very bad, where very good is the best state and grade very bad is the worst state. The proposed system procedure for overall assessment is shown in Figure 5.1, where the state condition and degree of membership for the lowest factor of the assessment criteria were described in detail chapter four.

Table 5.1:
State condition and recommended actions

State	State content	State condition
u_1	Very Good	The structural state of the building not damaged.
u_2	Good	The building as a whole is good, possibly some elements that do not affect the structural behavior may need repair. Continual monitoring is recommended
u_3	Moderate	The building as a whole is sound but some structural elements need repair. Continual observation is recommended
u_4	Bad	The building as a whole does not meet the requirements of the building code and needs to be strengthened; some elements may need to be strengthened immediately. Refer to refined safety diagnosis is recommended
u_5	Very Bad	The usage is prohibited and the building is unsafe and must be evacuated. Detailed investigation and full evaluation of the structural capacity of structural members also recommended.

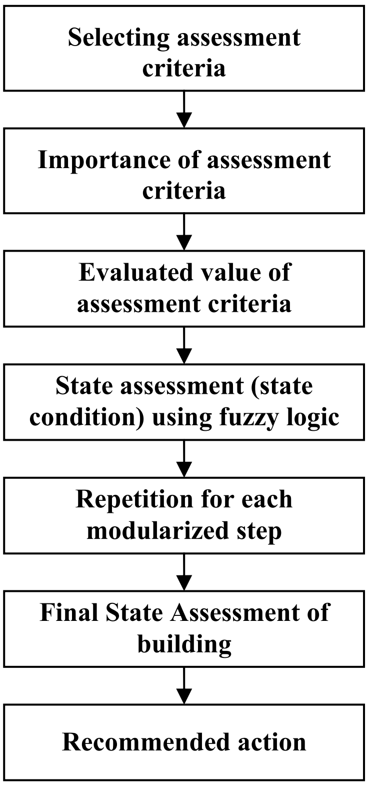

Figure 5.1: Procedure for designed expert system

The first step in designing the system is to select the assessment criteria and to identify their importance. If missing criteria exist, they are managed by re-estimating the importance of the available criteria. Then state assessment is carried out using a fuzzy logic with the evaluated results of the assessment criteria. This is repeated for each modularized step. Based on this, final state assessment and recommended action can be concluded.

To arrive at the goal sub-set representing the condition of a criterion it is necessary to combine its factors taking into account their relative importance. This is done by pre-multiplying the matrix of the degrees of membership by a vector representing the different weighting factors. For example, Building History state has four sub-criteria hence the matrix of membership values will have four rows and five columns (five categories). In addition, the weighting factors set from Figure 4.7 will be $W_{BH} = (0.154 \quad 0.311 \quad 0.280 \quad 0.255)$, and the goal sub set is computed by multiplying the weighting factor set by the matrix of membership values. The produced evaluation set $E = \{e_1, e_2, e_3, e_4, e_5\}$ for the goal and sub goal is a fuzzy set. The numerical values in set E are the degrees of membership correspond to the level of support to the different corresponding states.

5.4 SYSTEM IMPLEMENTATION

Computer programs with a graphical user interface (GUI) using MS Visual C sharp have been developed based on the formulations presented in the preceding sections. This program is easy to handle by users. They have to choose the condition state or fill the numeric value for the state conditions of the assessment criteria. Then the program will perform the needed calculations and provide the suitable condition state and the recommended action. The required inputs from the users/inspectors engineer are as following:

For Building History the user will choose the appropriate state corresponding to; 1) Shape and usage change, 2) Alteration of structural member, 3) Accident history and 4) Service years. And for Environmental Conditions it corresponds to; 1) Exposure to salt damage, 2) Exposure to high temperature and 3) Neighbor construction.

The inputs at lowest level of structural capacity are differ somewhat. For beam and slab, the user will input the required data related to; 1) Visual surface inspection, 2) Maximum crack width and 3) Deflection / span length %. While for columns and/or wall it is related to; 1) Visual surface inspection and 2) Maximum crack width. At the lowest level of Tilting and Settlement sub-criterion the user have to input the Story drift per story height % for each story in addition to State of soil settlement.

For durability main criteria, the inspector will input data for three sub-criteria. 1) Surface deterioration, which its required data is related to maximum depth of mortar loss for each column (scaling and / or spalling) and leakage state for each slab. 2) Corrosion state, which its required data are the bare corrosion state for each structural member and the corrosion exposure condition state. 3) Finishing material state, which its required data is related to exterior and interior finishing state. The fifth main criteria "professional involvement" has two sub criteria at the lowest level, where the user chooses the state of design and construction involvement.

A flow-chart of this computer program is shown in Figure 5.2, whereas Figures 5.3 shows the main screen of the software.

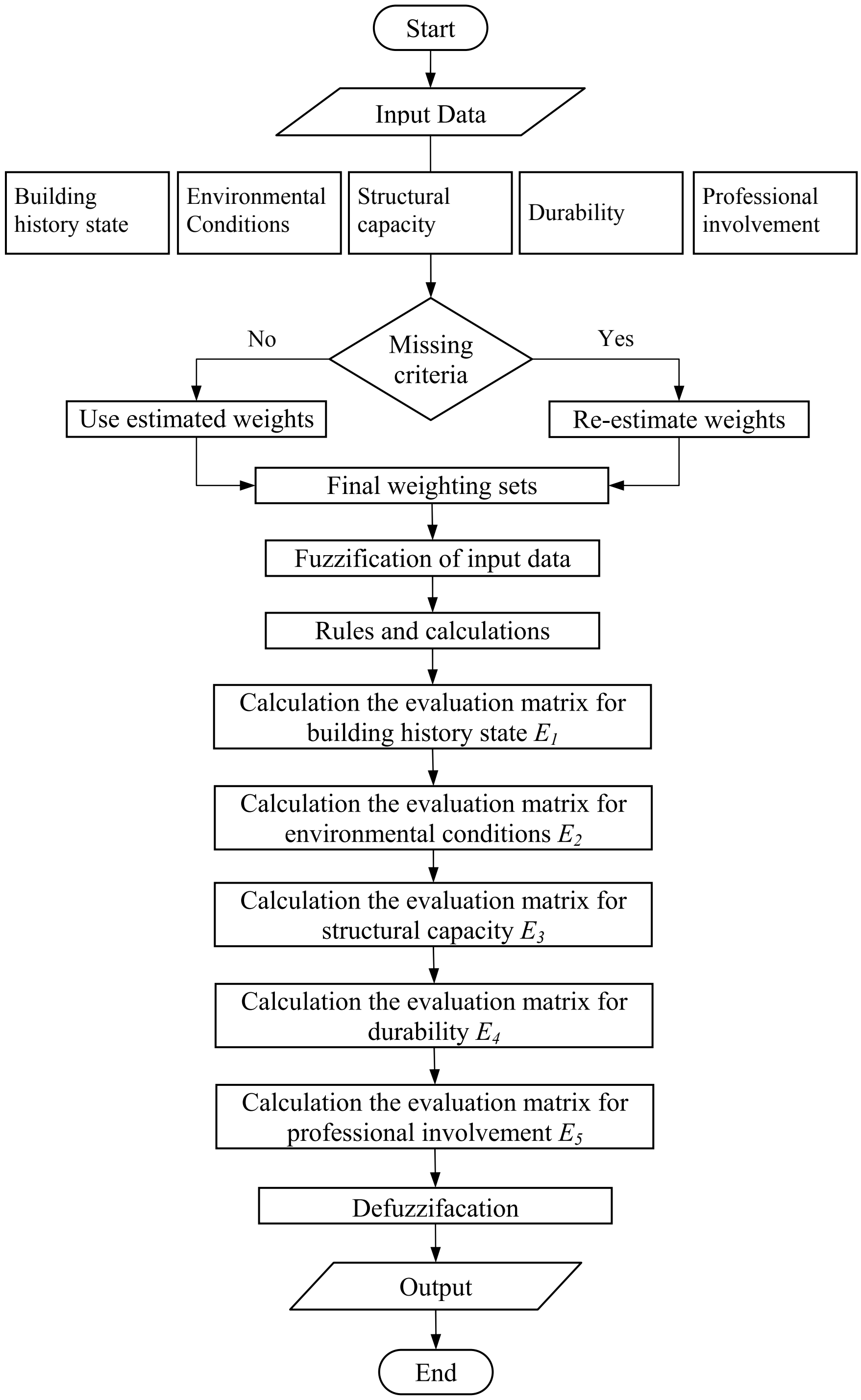

Figure 5.2: Flow-chart of computer program

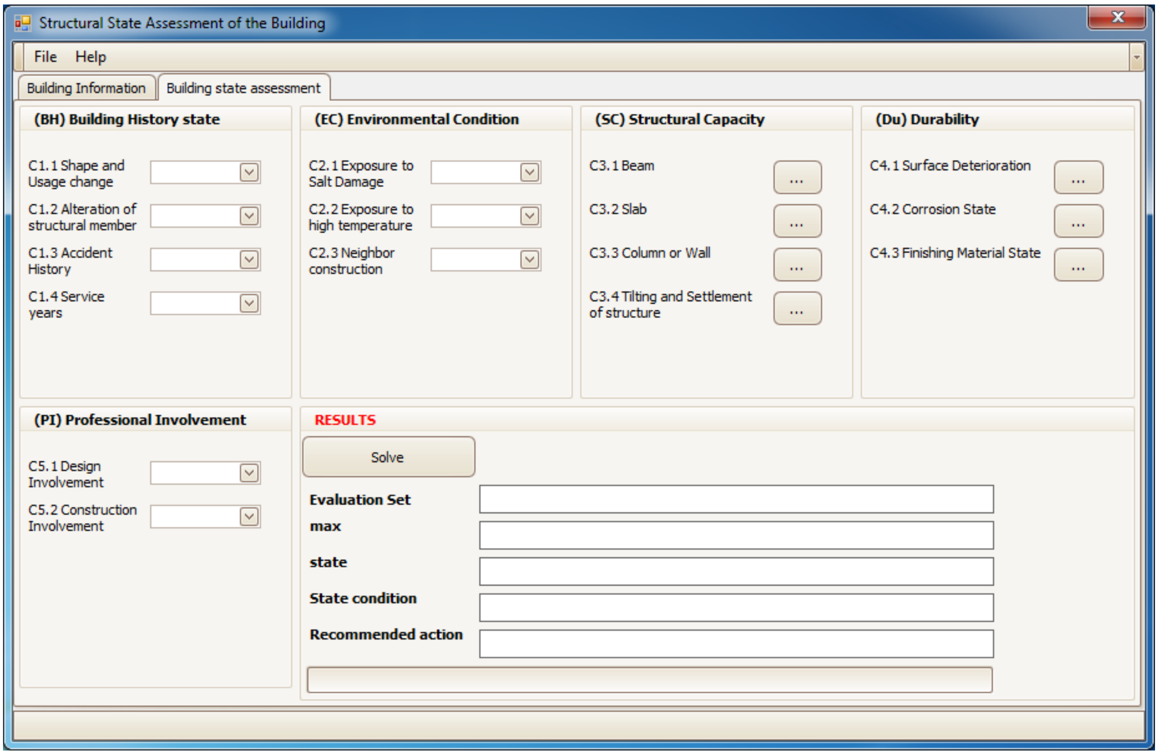

Figure 5.3: Main screen of the software

5.5 CASE STUDIES

Two case studies were chosen as the application examples to verify the applicability of design system. The first one extracted from literature, while the second is actual application case study of a building in Gaza strip.

5.5.1 Case study 1 (Two Story Framed Building)

1) Brief description of the structure

This case was studied by Lu and Simmonds [3] and applied to verify the designed system. It is for a building that was built in early 1920's used as a chemical plant, and is a two-story reinforced concrete framed building. The owners of the building plan to install new machines whose weights are to be larger than the previous ones. Therefore, the owners want to evaluate the overall structural condition and to propose some remedial action if necessary. Because of overloading and corrosion conditions, some of the reinforced concrete columns are cracked very severely, and the deflections of some beams are very large.

2) Available data

Design and construction quality of the building were believed to be average and poor respectively. In the same time, there are poor environmental conditions. Simplified profile of the structure and location of each structural member are shown in Figure 5.4. The beams, columns and footings are represented by *b*, *c* and *f* respectively.

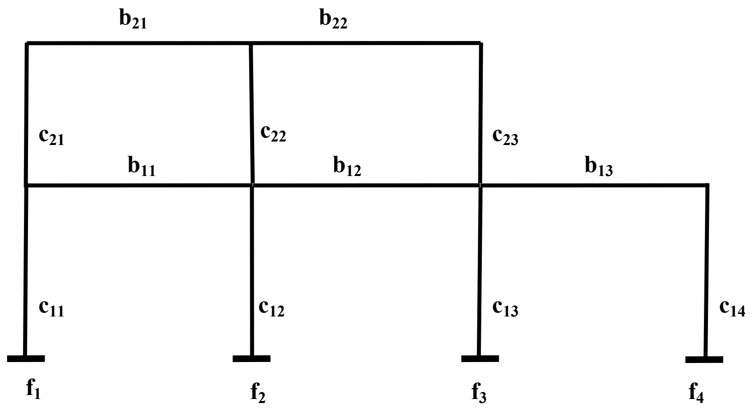

Figure 5.4: Simplified profile of case study 1

The available information for each element is shown in Table 5.2 as following;

Table 5.2:
Available information for each structural element of case study 1

Structural elements	Visual observation	Structural capacity	Maximum crack width (mm)	Max def. / span %	Story drift/story height
<u>Beams</u>					
b_{11}	Bad	0.76	> 1.0 mm	0. 63	…
b_{12}	Bad	0.70	> 1.0 mm	0. 81	…
b_{13}	Bad	0.78	> 1.0 mm	0. 6	…
b_{21}	Bad	0.81	> 1.0 mm	0.73	…
b_{22}	Bad	0.85	> 1.0 mm	7.0	…
<u>Slabs</u>					
S_{11}	Bad	0.78	> 1.0 mm	0. 6	
S_{12}	Bad	0.78	> 1.0 mm	0. 58	
S_{13}	Bad	0.75	> 1.0 mm	0. 53	
S_{21}	Bad	0.87	> 1.0 mm	0.53	
S_{22}	Poor	0.83	> 1.0 mm	0.57	
<u>Columns</u>					
C_{11}	Bad	0.80	> 1.0 mm	…	0.0035
C_{12}	Poor	0.76	0.95 mm	…	0.0032
C_{13}	Poor	0.78	0.90 mm	…	0.0033
C_{14}	Bad	0.85	> 1.0 mm	…	0.0038
C_{21}	Bad	0.85	> 1.0 mm	…	0.006
C_{22}	Poor	0.78	> 1.0 mm	…	0.005
C_{23}	Bad	0.83	> 1.0 mm	…	0.006
Structural elements	Visual observation	Structural capacity	Differential settlement	Slip from original position	
<u>Footing</u>					
f1	Poor	0.75	12 mm	19 mm	
f2	Poor	0.63	0 mm	15 mm	
f3	Poor	0.63	0 mm	15 mm	
f4	Poor	0.77	11 mm	16 mm	

3) Assessment by Lu and Simmonds

Lu and Simmonds [3] proposed a methodology for developing a knowledge-based expert system (KBES) for assessing the structural condition of existing reinforced concrete framed buildings. For the goal set, four states are used, $U = \{u_1, u_2, u_3, u_4\}$. These states are; Good, average, poor, bad.

In addition to the results of field observations, the procedure incorporates the strength computations of individual members and combines these using weighting factors to obtain the overall structural condition. Structural capacity (ratio of provided capacity to required capacity) of each structural member (i.e. footings, columns, beams, and slabs), and differential settlement and slip from original position of each footing are used in the solution of the problem. According to the provided KBES, the overall structural condition of the building is u_4, which corresponds to state condition bad.

4) Assessment by the proposed system

The input values to the proposed system in this study are extracted from the previous mention available data. Keeping in mind the proposed system are based on close visual observation, thereby not all of the available data will be used. The required data would be extracted from Table 5.2 in order to evaluate fuzzy values for each assessment category. The calculated values and final assessment results are shown in Tables 5.3

Table 5.3
Evaluated fuzzy matrices for case study 1

Assessment categories	**Assessment criteria**		**Re-estimated weights**	**Evaluation fuzzy matrix (E_i)**				
Building History state	C1.1 Shape and Usage change		--	0.0	0.0	0.0	0.0	0.0
	C1.2 Alteration of structural member		--	0.0	0.0	0.0	0.0	0.0
	C1.3 Accident History		--	0.0	0.0	0.0	0.0	0.0
	C1.4 Service years		1.0	0.0	0.0	0.118	0.294	0.588
	Evaluation sub-set for building history state (E_1):			**0.0**	**0.0**	**0.118**	**0.294**	**0.588**
Environmenta Conditions	C2.1 Exposure to salt damage		1.0	0.0	0.0	0.111	0.333	0.556
	C2.2 Exposure to high temperature		--	0.0	0.0	0.0	0.0	0.0
	C2.3 Neighbor constructions		--	0.0	0.0	0.0	0.0	0.0
	Evaluation sub-set for environmental conditions (E_2):			**0.0**	**0.0**	**0.111**	**0.333**	**0.556**
Structural Capacity	C3.1 Beam (0.238)	C3.1.1 Visual surface inspection	0.412	0	0.0	0.273	0.455	0.273
		C3.1.2 Crack width	0.325	0	0.0	0.0	0.50	0.50
		C3.1.3 Deflection	0.263	0	0.0	0.0	0.40	0.60
		Evaluation sub-set for beams:		**0.0**	**0.0**	**0.112**	**0.455**	**0.433**
	C3.2 Slab (0.185)	C3.2.1 Visual surface inspection	0.412	0.000	0.000	0.250	0.427	0.323
		C3.2.2 Crack width	0.325	0	0.0	0.0	0.40	0.60
		C3.2.3 Deflection	0.263	0	0.0	0.40	0.40	0.20
		Evaluation sub-set for slabs:		**0.0**	**0.0**	**0.208**	**0.411**	**0.381**

	C3.3 Column (0.334)	C3.3.1 Visual surface inspection	0.684	0.0	0.0	0.224	0.395	0.381
		C3.3.2 Crack width	0.316	0.0	0.0	0.0	0.286	0.714
		Evaluation sub-set for columns:		**0.0**	**0.0**	**0.153**	**0.361**	**0.487**
	C3.4 tilting & settlement (0.242)	C3.4.1 Tilting of structure	0.433	0.5	0.5	0.0	0.0	0.0
		C3.4.2 Settlement of soil	0.567	0.038	0.269	0.385	0.269	0.038
	Evaluation sub-set for tilting and settlement:			**0.238**	**0.369**	**0.218**	**0.153**	**0.022**
Evaluation sub-set for structural capacity (***E***$_3$):				**0.058**	**0.089**	**0.169**	**0.342**	**0.342**
Durability	C4.1 Surface Deterioration	C4.1.1 Scaling / Spalling	--					
		C4.1.2 leakage	--					
	C4.2 Corrosion State	C4.2.1 Bar corrosion	--					
		C4.2.2 Corrosion Exposure Conditions	--					
	C4.3 Finishing Material	C4.3.1 Exterior Finishing	--					
		C4.3.2 Interior Finishing	--					
Evaluation sub-set for Durability (***E***$_4$):				**0.00**	**0.00**	**0.00**	**0.00**	**0.00**
Professional Involvement	C5.1 Design involvement		0.5	0.0	0.25	0.50	0.25	0.0
	C5.2 Construction involvement		0.5	0.0	0.0	0.143	0.286	0.571
Evaluation sub-set for Professional Involvement (***E***$_5$):				**0.00**	**0.125**	**0.321**	**0.268**	**0.286**
Fuzzy evaluation matrix for the goal, building structural state assessment, is composed of E_1, E_2, E_3, E_4 and E_5				**0.0**	**0.0**	**0.118**	**0.294**	**0.588**
				0.0	**0.0**	**0.111**	**0.333**	**0.556**
				0.058	**0.089**	**0.169**	**0.342**	**0.342**
				0.00	**0.00**	**0.00**	**0.00**	**0.00**
				0.00	**0.125**	**0.321**	**0.268**	**0.286**
The re-estimated over all weighting factor				**0.143**	**0.175**	**0.598**	**0.00**	**0.084**
The final evaluation set *E*				**0.035**	**0.064**	**0.164**	**0.327**	**0.410**

-- missing criteria

Because $e_5 = 0.410$ is the maximum value within the set E, the overall structural condition of the building is u_5, that represent state content , and condition from Table 5.1 as follow;

State content	State condition
Very Bad	The usage prohibition and the building are unsafe and must be vacated.

The output of KBES presented by Lu and Simmonds was Poor, which represent the most severe state. In addition, the output of proposed expert system of this study was Very Bad, which represent also the most severe case. From these results it can be concluded that, although the KBES presented by Lu and Simmonds based on detailed investigation and testing and the presented proposed system based only close visual observation and simple measurements that do not require special testing, the output of each system is much close.

5.5.2 Case study 2 (Two Story Skeleton Building)

1) Brief description

The chosen practical case study located in Biet Lahia North Gaza. It was constructed in 2005 as the owner declared. Its total area estimated about 150 m^2 consisted of two-story reinforced concrete skeleton system with one-way ribbed slab on beams supported on columns that transform loads to foundations. The ground floor is a mezzanine, while the first floor is housing flat. A sketch plan and section of the building is shown in Figure 5.5.

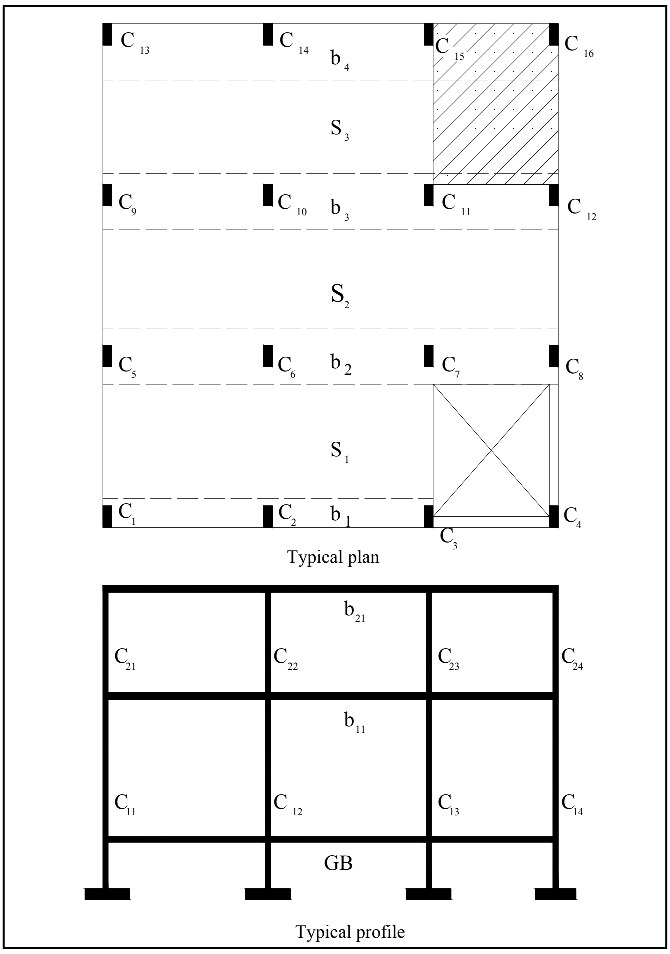

Figure 5.5: Sketch plan and simplified profile of case study 2

The building was damaged by Israeli missiles during the war on Dec 2008-Jan 2009. Total destruction of the dashed area was due the missile that hit it directly. In addition to that, severe damages to most structural members of the building observed, where the columns number (C1, C5 and C16) in ground floor was completely fractured consequently slabs were severely cracked. As a result of the missile in the first floor, there was big fire that produced a high temperature and caused spalling of plastering. Moreover, some partition and external walls were destroyed. An engineering team of Ministry of Public Works and Housing (MPWH) had done a fast assessment after the war ending. As an urgent action, the team asks the owner to evacuate and shore up the building. During the preceding period in addition to MPWH, a consulting firm contributes in the assessment. The teams to decide whether to demolish or to repair had conducted a lot of tests and investigations. The teams could not reach a decision regarding the existing actual state of the building.

2) Available data

As a case study of this research, a site visit and visual inspection was carried out. The inspections were noted from site observations and used as inputs to the proposed system.

The input values to the system are as following

Building History state:		
	Shape and Usage change	Good
	Alteration of structural member	moderate
	Accident History	Very bad
	Service years	Very good
Environmental Conditions:		
	Exposure to Salt Damage	Good
	Exposure to high temperature	Moderate
	Neighbor construction	Very good
Durability		
	Corrosion Exposure Conditions	moderate
	Exterior Finishing	----
	Interior Finishing	Very bad
Professional Involvement		
	Design involvement	good
	Construction involvement	very bad

Meanwhile, for each structural element the input data are listed in Table 5.4

Table 5.4:
Available information for each structural element of case study 2

Beams	Visual surface inspection	Crack width (mm)	Deflection (mm)	Span length (mm)	Def./ span %
b_{11}	Very Bad	Visible (≈ 0.8)	50	4500	1.11
b_{12}	Bad	Hair (≤0.4)	40	4500	0.88
b_{13}	Good	Hair (≤0.4)	<15	4500	<0.33
b_{14}	Very bad	Severe			
b_{21}	Bad	Hair (≤0.4)	25	4500	0.55
b_{22}	Bad	Hair (≤0.4)	20	4500	0.44
b_{23}	Moderate	Hair (≤0.4)	<15	4500	<0.33
b_{24}	Very bad	Severe			

Slabs	Visual surface inspection	Max. crack width (mm)	Deflection (mm)	Span length (mm)	Def./ span %	leakage
S_{11}	Bad	Severe (≈2)	50	4500	1.11	good
S_{12}	Moderate	Hair (≤0.4)	<15	4500	<0.33	bad
S_{13}	Very bad	Severe				good
S_{21}	Bad	Severe(≈3)	40	4500	1.11	good
S_{22}	Moderate	Hair (≤0.4)	<15	4500	<0.33	bad
S_{23}	Very bad	Severe				bad
Columns	Visual surface inspection	Max. crack width (mm)	Spalling (mm)			
C_{11}	Very bad	Severe	Very severe			
C_{12}	Moderate	Hair (≤0.4)	Very severe			
C_{13}	Good	Hair (≤0.4)	No			
C_{14}	Good	Hair (≤0.4)	No			
C_{15}	Very bad	Severe	Very severe			
C_{16}	Good	Hair (≤0.4)	No			
C_{17}	Good	Hair (≤0.4)	No			
C_{18}	Moderate	Hair (≤0.4)	No			
C_{19}	Very bad	Severe	No			
C_{110}	Good	Hair (≤0.4)	Light			
C_{111}	Bad	Small (≈0.6)	light			
C_{112}	Very bad	Severe	Very severe			
C_{113}	Good	Hair (≤0.4)	No			
C_{114}	Good	Hair (≤0.4)	No			
C_{115}	Very bad	Severe	Very severe			
C_{16}	Very bad	Severe	Very severe			
C_{21}	Moderate	Hair (≤0.4)	No			
C_{22}	Moderate	Hair (≤0.4)	No			
C_{23}	Good	Hair (≤0.4)	No			
C_{24}	Good	Hair (≤0.4)	No			
C_{25}	Moderate	Hair (≤0.4)	No			
C_{26}	Moderate	Hair (≤0.4)	No			
C_{27}	Very good	Hair (≤0.4)	No			
C_{28}	Very good	Hair (≤0.4)	No			
C_{29}	Moderate	Hair (≤0.4)	No			
C_{210}	Very good	Hair (≤0.4)	Light			
C_{211}	Bad	Small (≈0.6)	Light			
C_{212}	Bad	Small (≈0.6)	Light			
C_{213}	Very good	Hair (≤0.4)	No			
C_{214}	Very good	Hair (≤0.4)	No			
C_{215}	Bad	Small (≈0.6)	Very severe			
C_{216}	Very bad	Severe	Very severe			

5) Assessment by the proposed system

The available information is applied to the proposed system in order to determine the structural state of the building. The calculated fuzzy values for each assessment category and the final assessment results are in Tables 5.5.

Table 5.5:
Evaluated fuzzy matrices for case study 2

Assessment categories	Assessment criteria		Re-estimated weights	Evaluation fuzzy matrix (E_i)				
Building History state	C1.1 Shape and Usage change		0.154	0.25	0.50	0.25	0.00	0.00
	C1.2 Alteration of structural member		0.311	0.04	0.22	0.45	0.22	0.045
	C1.3 Accident History		0.280	0.00	0.00	0.11	0.29	0.588
	C1.4 Service years		0.256	0.588	0.294	0.118	0.000	0.000
	Evaluation sub-set for building history state (E_1):			**0.203**	**0.223**	**0.243**	**0.153**	**0.179**
Environmental Conditions	C2.1 Exposure to salt damage		0.393	0.261	0.435	0.261	0.043	0.000
	C2.2 Exposure to high temperature		0.441	0.000	0.273	0.455	0.273	0.000
	C2.3 Neighbor constructions		0.167	0.556	0.333	0.111	0.000	0.000
	Evaluation sub-set for environmental conditions (E_2):			**0.195**	**0.346**	**0.321**	**0.137**	**0.000**
Structural Capacity	C3.1 Beam (0.238)	C3.1.1 Visual surface inspection	0.412	0.039	0.088	0.248	0.320	0.305
		C3.1.2 Crack width	0.325	0.563	0.063	0.125	0.000	0.250
		C3.1.3 Deflection	0.263	0.25	0	0.125	0	0.625
		Evaluation sub-set for beams:		**0.265**	**0.057**	**0.135**	**0.132**	**0.412**
	C3.2 Slab (0.185)	C3.2.1 Visual surface inspection	0.412	0.014	0.083	0.282	0.340	0.280
		C3.2.2 Crack width	0.325	0.167	0.167	0.000	0.000	0.667
		C3.2.3 Deflection	0.263	0.167	0.093	0.074	0.000	0.667
		Evaluation sub-set for slabs:		**0.104**	**0.113**	**0.136**	**0.140**	**0.508**
	C3.3 Column (0.334)	C3.3.1 Visual surface inspection	0.684	0.158	0.221	0.256	0.193	0.173
		C3.3.2 Crack width	0.316	0.719	0.063	0.000	0.000	0.219
		Evaluation sub-set for columns:		**0.335**	**0.171**	**0.175**	**0.132**	**0.187**
	C3.4 tilting & settlement (0.242)	C3.4.1 Tilting of structure	---					
		C3.4.2 Settlement of soil	1.0	0.000	0.040	0.280	0.400	0.280
	Evaluation sub-set for tilting and settlement:			**0**	**0.04**	**0.28**	**0.4**	**0.28**
	Evaluation sub-set for structural capacity (E_3):			**0.194**	**0.101**	**0.184**	**0.199**	**0.323**
Durability	C4.1 Surface Deterioration	C4.1.1 Scaling / Spalling	0.684	0.297	0.375	0.078	0.016	0.234
		C4.1.2 leakage	0.316	0.130	0.239	0.261	0.239	0.130
		Evaluation sub-set for surface deterioration		**0.244**	**0.332**	**0.136**	**0.086**	**0.202**
	C4.2 Corrosion State	C4.2.1 Bar corrosion	0.684	0.079	0.190	0.238	0.333	0.159
		C4.2.2 Corrosion Exposure Conditions	0.316	0.045	0.227	0.455	0.227	0.045
		Evaluation sub-set for corrosion state		**0.069**	**0.202**	**0.306**	**0.300**	**0.123**
	C4.3 Finishing Material	C4.3.1 Exterior Finishing	--					
		C4.3.2 Interior Finishing	1.0	0.000	0.000	0.118	0.294	0.588
		Evaluation sub-set for Finishing material		**0.000**	**0.000**	**0.118**	**0.294**	**0.588**
	Evaluation sub-set for Durability (E_4):			**0.126**	**0.219**	**0.208**	**0.215**	**0.231**

Professional Involvement	C5.1 Design involvement	0.5	0.25	0.50	0.25	0.00	0.00
	C5.2 Construction involvement	0.5	0.000	0.000	0.143	0.286	0.571
	Evaluation sub-set for Professional Involvement (***E_5***):		**0.125**	**0.25**	**0.196**	**0.143**	**0.286**
Fuzzy evaluation matrix for the goal, building structural state assessment, is composed of E_1, E_2, E_3, E_4 and E_5			**0.203**	**0.223**	**0.243**	**0.153**	**0.179**
			0.195	**0.346**	**0.321**	**0.137**	**0.000**
			0.194	**0.101**	**0.184**	**0.199**	**0.323**
			0.120	**0.207**	**0.197**	**0.205**	**0.226**
			0.125	**0.250**	**0.196**	**0.143**	**0.286**
The re-estimated over all weighting factor			**0.106**	**0.125**	**0.468**	**0.231**	**0.069**
The final evaluation set *E*			**0.175**	**0.182**	**0.214**	**0.186**	**0.243**

-- missing criteria

The maximum value within the set *E* is e_5 = 0.243, thereby the overall structural condition of the building is u_5. This state condition represents state content and condition from Table 5.1 as follow;

State content	State condition
Very Bad	The usage is prohibited and the building is unsafe and must be evacuated. Detailed investigation and full evaluation of the structural capacity of structural members also recommended.

CHAPTER SIX:
SUMMARY AND CONCLUSIONS

6.1 SUMMARY

The primary objective of this study was to develop an effective structural evaluation system for reinforced concrete buildings in Gaza Strip with sufficient flexibility to allow an inexperienced engineer to work in the field of structural assessment. This study developed a methodology for combining field observations, numerical calculations and structural expertise, where it gave a mathematical significance to the results of visual observations that are often expressed in linguistic terms. The assessment of damage state of structures is inherently subject to vagueness, ambiguity and consequently to uncertainty, where subjective opinion and incomplete numeric data are unavoidable. Thereby, the uncertainties, which produced due to the use of linguistic terms for defining the building conditions state and quality of construction, were handled using fuzzy sets theory. Using fuzzy logic provided a mathematical way to represent vagueness and fuzziness in humanistic systems.

The final state of the assessed building was divided into five grades; very good, good, moderate, bad, and very bad. However, in order to determine damage state, the decisions was made based on the weighting that given to the different assessment criteria. The selected assessment criteria was studied and identified based on close visual inspections and simple measurements that do not require special testing or long-term investigation. They were classified hierarchically according to assessment divisions. At goal level, the problem was divided into a level of simpler problems, which, in turn, were subdivided into even simpler problems at corresponding lower levels. This process was repeated until a level was reached in which the problems or questions posed could be answered by the. The main criteria, which considered are; building history state, environmental conditions, structural capacity, durability, and professional involvement. Fuzzy Analytic Hierarchy Process method was utilized to estimate the weights of assessment criteria.

The chosen criteria were formalized quantitatively using fuzzy logic concepts with reference to technical books, building codes, former research, and properties of building materials. The inputs to the system are inspection results, mostly linguistic variables, and some numeric data concerning the selected categories for the assigned criterion. These inputs were expressed as fuzzy sets with appropriate membership values and then were combined using weighting factors and fuzzy composition. In this step-by-step way, inputs are obtained for each successive level until the answer to the highest level or originally posed problem is obtained. This modularized stepwise assessment had the advantages of enhancing the efficiency and reliability of assessment and flexibility concerning missing or inadequate criteria.

Two case studies were used to verify the applicability of the designed system. The results obtained by the proposed system showed consistent conclusions with the opinion of experts. The developed system expected to be used as an effective tool to determine the structural state of reinforced concrete building in Gaza strip.

6.2 CONCLUSIONS

- An effective structural assessment expert system for evaluation of reinforced concrete buildings using fuzzy logic was developed in this study.
- The developed system was implemented in a graphical user interface (GUI) software program that is easy to handle by users.
- The developed system would certainly help the engineers, policy makers, owners and stakeholders concerned buildings assessment to arrive at a systematic judgement and to formulate methodical steps towards assessing the structural state of the buildings.
- According to the study, the most important criterion of the main criteria was the structural capacity of the building with a weighting 46.8%, then durability with a weighting 23.2%. The weightings of environmental conditions, building history state and professional involvement were 12.5%, 10.6%, and 6.9% respectively.
- It is recommended that the importance of each assessment criterion derived in this study should not be used as a fixed value but needs to be amended from time to time and from accident to accident to better reflect the situation characteristics and the opinion of the experts.
- Misperception of the structure's conditions and requirements, misstatement of the inspectors and/or the absence of information may cause the proposed system recommendations to be invalid. This is why users are encouraged to be trained deeply before using the developed expert system.
- Although the presented expert system was based on close visual inspections and simple measurements, it would pave the way for future research on condition evaluation of existing structures based on detailed investigations, and it may provide substantial assistance to more complicated works.
- It is recommended to conduct further research for evaluation scheme that based on detailed investigations.

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APPENDIX A:
Interview Question Form

Read the following questions and put check marks on the pair-wise comparison matrices. If a criterion on the left is more important than the one matching on the right, put your check mark to the left of the importance ‘‘Equal’’ under the importance level you prefer. If a criterion on the left is less important than the one matching on the right, put your check mark to the right of the importance ‘‘Equal’’ under the importance level you prefer.

<u>QUESTIONS</u>

With respect to the overall goal ‘‘**Structural State Assessment of the Building**’’;

Q1. How important is Building History (B.H) when it is compared with Environmental Condition (E.C)?

Q2. How important is Building History (B.H) when it is compared with Structural Capacity (S.C)?

Q3. How important is Building History (B.H) when it is compared with Durability (Du)?

Q4. How important is Building History (B.H) when it is compared with Professional Involvement (P.I)?

Q5. How important is Environmental Condition (E.C) when it is compared with Structural Capacity (S.C)?

Q6. How important is Environmental Condition (E.C) when it is compared with Durability (Du)?

Q7. How important is Environmental Condition (E.C) when it is compared with Professional Involvement (P.I)?

Q8. How important is Structural Capacity (S.C) when it is compared with Durability (Du.)?

Q9. How important is Structural Capacity (S.C) when it is compared with Professional Involvement (P.I)?

Q10. How important is Durability (Du.) when it is compared with Professional Involvement (P.I)?

With respect to: “Building Structural Assessment”	Importance (or preference) of one main-criterion over another										
Questions	Criteria	Absolute (2,5/2,3)	Very strong (3/2, 2, 5/2)	Strong (1, 3/2, 2)	Moderate (1/2, 1, 3/2)	Equal (1, 1, 1)	Moderate (2/3, 1, 2)	Strong (1/2, 2/3, 1)	Very strong (2/5, 1/2, 2/3)	Absolute (1/3, 2/5, 1/2)	Criteria
Q1	B.H										E.C
Q2	B.H										S.C
Q3	B.H										Du.
Q4	B.H										P.I

With respect to: "Building Structural Assessment"	Importance (or preference) of one main-criterion over another										
Questions	Criteria	Absolute (2,5/2,3)	Very strong (3/2, 2, 5/2)	Strong (1, 3/2, 2)	Moderate (1/2, 1, 3/2)	Equal (1, 1, 1)	Moderate (2/3, 1, 2)	Strong (1/2, 2/3, 1)	Very strong (2/5, 1/2, 2/3)	Absolute (1/3, 2/5, 1/2)	Criteria
Q5	E.C										S.C
Q6	E.C										Du.
Q7	E.C										P.I
Q8	S.C										Du.
Q9	S.C										P.I
Q10	Du.										P.I

With respect to the main criterion ''**Building History State (B.H)**'';

Q11. How important is Shape and usage change (C1.1) when it is compared with Alteration of structural member (C1.2)?

Q12. How important is Shape and usage change (C1.1) when it is compared with accident history (C1.3)?

Q13. How important is Shape and usage change (C1.1) when it is compared with service years (C1.4)?

Q14. How important is Alteration of structural member (C1.2) when it is compared with accident history (C1.3)?

Q15. How important is Alteration of structural member (C1.2) when it is compared with service years (C1.4)?

Q16. How important is accident history (C1.3) when it is compared with service years (C1.4)?

With respect to: "Building History State"	Importance (or preference) of one Sub-criterion over another										
Questions	Criteria	Absolute (2,5/2,3)	Very strong (3/2, 2, 5/2)	Strong (1, 3/2, 2)	Moderate (1/2, 1, 3/2)	Equal (1, 1, 1)	Moderate (2/3, 1, 2)	Strong (1/2, 2/3, 1)	Very strong (2/5, 1/2, 2/3)	Absolute (1/3, 2/5, 1/2)	Criteria
Q11	C1.1										C1.2
Q12	C1.1										C1.3
Q13	C1.1										C1.4
Q14	C1.2										C1.3
Q15	C1.2										C1.4
Q16	C1.3										C1.4

With respect to the main criterion ‘‘**Environmental condition (E.C)**’’;

Q17. How important is exposure to Salt Damage (C2.1) when it is compared with exposure to high temperature or vibration (C2.2)?
Q18. How important is exposure to Salt Damage (C2.1) when it is compared with neighbor construction (C2.3)?
Q19. How important is exposure to high temperature or vibration (C2.2) when it is compared with neighbor construction (C2.4)?

With respect to: “Environmental condition”	Importance (or preference) of one Sub-criterion over another											
Questions	Criteria	Absolute (2,5/2,3)	Very strong (3/2, 2, 5/2)	Strong (1, 3/2, 2)	Moderate (1/2, 1, 3/2)	Equal (1, 1, 1)	Moderate (2/3, 1, 2)	Strong (1/2, 2/3, 1)	Very strong (2/5, 1/2, 2/3)	Absolute (1/3, 2/5, 1/2)	Criteria
Q17	C2.1										C2.2
Q18	C2.1										C2.3
Q19	C2.2										C2.3

With respect to the main criterion ‘‘**Structural Capacity (S.C)**’’;

Q20. How important is Beam (C3.1) when it is compared with Slab (C3.2)?
Q21. How important is Beam (C3.1) when it is compared with Column or wall (C3.3)?
Q22. How important is Beam (C3.1) when it is compared with tilting and settlement of structure (C3.4)?
Q23. How important is Slab (C3.2) when it is compared with Column or wall (C3.3)?
Q24. How important is Slab (C3.2) when it is compared with tilting and settlement of structure (C3.4)?
Q25. How important is Column or wall (C3.3) when it is compared with tilting and settlement of structure (C3.4)?

With respect to: “Structural Capacity”	Importance (or preference) of one Sub-criterion over another											
Questions	Criteria	Absolute (2,5/2,3)	Very strong (3/2, 2, 5/2)	Strong (1, 3/2, 2)	Moderate (1/2, 1, 3/2)	Equal (1, 1, 1)	Moderate (2/3, 1, 2)	Strong (1/2, 2/3, 1)	Very strong (2/5, 1/2, 2/3)	Absolute (1/3, 2/5, 1/2)	Criteria
Q20	C3.1										C3.2
Q21	C3.1										C3.3
Q22	C3.1										C3.4
Q23	C3.2										C3.3
Q24	C3.2										C3.4
Q25	C3.3										C3.4

With respect to the main criterion ‘‘**Durability (Du.)”;**

Q26. How important is Surface Deterioration (C4.1) when it is compared to Corrosion state (C4.2)?

Q27. How important is Surface Deterioration (C4.1) when it is compared to Finishing Material State (C4.3)?

Q28. How important is Corrosion State (C4.2) when it is compared to Finishing Material State (C4.3)?

With respect to: “Durability”	Importance (or preference) of one Sub-criterion over another										
Questions	Criteria	Absolute (2,5/2,3)	Very strong (3/2, 2, 5/2)	Strong (1, 3/2, 2)	Moderate (1/2, 1, 3/2)	Equal (1, 1, 1)	Moderate (2/3, 1, 2)	Strong (1/2, 2/3, 1)	Very strong (2/5, 1/2, 2/3)	Absolute (1/3, 2/5, 1/2)	Criteria
Q26	C4.1										C4.2
Q27	C4.1										C4.3
Q28	C4.2										C4.3

With respect to the main criterion **‘‘Professional Involvement (P.I)**”

Q29. How important is design involvement (C5.1) when it is compared to construction involvement (C5.2)?

With respect to: “Professional Involvement”	Importance (or preference) of one Sub-criterion over another										
Questions	Criteria	Absolute (2,5/2,3)	Very strong (3/2, 2, 5/2)	Strong (1, 3/2, 2)	Moderate (1/2, 1, 3/2)	Equal (1, 1, 1)	Moderate (2/3, 1, 2)	Strong (1/2, 2/3, 1)	Very strong (2/5, 1/2, 2/3)	Absolute (1/3, 2/5, 1/2)	Criteria
Q29	C5.1										C5.2

With respect to the Sub criteria **‘‘Beam (C3.1) and Slab (C3.2)”;**

Q30. How important is Visual Surface Inspection (C3.x.1) when it is compared with crack width (C3.x.2?

Q31. How important is Visual Surface Inspection (C3.x.1) when it is compared with Deflection (C3.x.3)

Q32. How important is crack width (C3.x.2) when it is compared with Deflection (C3.x.3)?

With respect to: “(C3.1) and (C3.2)	Importance (or preference) of one Sub-subcriterion over another										
Questions	Criteria	Absolute (2,5/2,3)	Very strong (3/2, 2, 5/2)	Strong (1, 3/2, 2)	Moderate (1/2, 1, 3/2)	Equal (1, 1, 1)	Moderate (2/3, 1, 2)	Strong (1/2, 2/3, 1)	Very strong (2/5, 1/2, 2/3)	Absolute (1/3, 2/5, 1/2)	Criteria
Q30	C3.x.1										C3.x.2
Q31	C3.x.1										C3.x.3
Q32	C3.x.2										C3.x.3

With respect to the Sub criteria ‘‘**Column or wall (C3.3)”;**

Q33. How important is Visual Surface Inspection (C3.3.1) when it is compared with crack width (C3.3.2)?

With respect to: ‘‘Column or wall (C3.3)”	Importance (or preference) of one Sub-subcriterion over another									
Questions	Criteria	Absolute (2,5/2,3)	Very strong (3/2, 2, 5/2)	Strong (1, 3/2, 2)	Moderate (1/2, 1, 3/2)	Equal (1, 1, 1)	Moderate (2/3, 1, 2)	Strong (1/2, 2/3, 1)	Very strong (2/5, 1/2, 2/3)	Absolute (1/3, 2/5, 1/2)	Criteria
Q33	C3.3.1										C3.3.2

With respect to the Sub criteria ‘‘**Tilting and Settlement (C3.4)”;**

Q34. How important is tilting of structure (C3.4.1) when it is compared with settlement of soil (C3.4.2)?

With respect to: “Tilting and Subsidence (C3.3)”	Importance (or preference) of one Sub-subcriterion over another									
Questions	Criteria	Absolute (2,5/2,3)	Very strong (3/2, 2, 5/2)	Strong (1, 3/2, 2)	Moderate (1/2, 1, 3/2)	Equal (1, 1, 1)	Moderate (2/3, 1, 2)	Strong (1/2, 2/3, 1)	Very strong (2/5, 1/2, 2/3)	Absolute (1/3, 2/5, 1/2)	Criteria
Q34	C3.3.1										C3.3.2

With respect to the Sub criteria ‘‘**Surface deterioration (C4.1)”;**

Q35. How important is spalling (C4.1.1) when it is compared with leakage (C4.1.2)?

With respect to: “Surface deterioration (C4.1)”	Importance (or preference) of one Sub-subcriterion over another									
Questions	Criteria	Absolute (2,5/2,3)	Very strong (3/2, 2, 5/2)	Strong (1, 3/2, 2)	Moderate (1/2, 1, 3/2)	Equal (1, 1, 1)	Moderate (2/3, 1, 2)	Strong (1/2, 2/3, 1)	Very strong (2/5, 1/2, 2/3)	Absolute (1/3, 2/5, 1/2)	Criteria
Q35	C4.1.1										C4.1.2

With respect to the Sub criteria ‘‘**Corrosion State (C4.2)”**

Q36. How important is Bar Corrosion (C4.2.1) when it is compared with Corrosion exposure condition (C4.2.2)

With respect to: “corrosion State (C4.2)”	Importance (or preference) of one Sub-subcriterion over another										
Questions	Criteria	Absolute (2,5/2,3)	Very strong (3/2, 2, 5/2)	Strong (1, 3/2, 2)	Moderate (1/2, 1, 3/2)	Equal (1, 1, 1)	Moderate (2/3, 1, 2)	Strong (1/2, 2/3, 1)	Very strong (2/5, 1/2, 2/3)	Absolute (1/3, 2/5, 1/2)	Criteria
Q36	C4.2.1										C4.2.2

With respect to the Sub criteria **‘‘Finishing Material State (C4.3)”;**

Q37. How important is Exterior Finishing Material (C4.3.1) when it is compared with Interior Finishing Material (C4.3.2)?

With respect to: “Finishing Material state (C4.3)”	Importance (or preference) of one Sub-subcriterion over another										
Questions	Criteria	Absolute (2,5/2,3)	Very strong (3/2, 2, 5/2)	Strong (1, 3/2, 2)	Moderate (1/2, 1, 3/2)	Equal (1, 1, 1)	Moderate (2/3, 1, 2)	Strong (1/2, 2/3, 1)	Very strong (2/5, 1/2, 2/3)	Absolute (1/3, 2/5, 1/2)	Criteria
Q37	C4.3.1										C4.3.2

APPENDIX B:
Pairwise Comparison for Second and Third Level Criteria

B.1 Pairwise Comparisons of First Level Sub-Criteria

B.1.1 Building History State (BH)

Table B. 1: The fuzzy evaluation matrix with respect to Building History State (BH)

	C1.1	C1.2	C1.3	C1.4
C1.1	(1, 1, 1)	(1/2,2/3, 1)	(1/2,2/3, 1)	(1/2, 2/3, 1)
C1.2	(1, 3/2, 2)	(1, 1, 1)	(1, 1, 1)	(1, 3/2, 2)
C1.3	(1, 3/2, 2)	1, 1, 1)	(1, 1, 1)	(2/3, 1, 2)
C1.4	(1, 3/2, 2)	(1/2, 2/3,1)	(1/2, 1, 3/2)	(1, 1, 1)

The normalized weight vector with respect to Building History State is obtained as:

Criterion	C1.1	C1.2	C1.3	C1.4
W %	15.4%	31.1%	28%	25.5%

B.1.2 Environmental Condition (EC)

Table B. 2: The fuzzy evaluation matrix with respect to Environmental Condition (EC)

	C2.1	C2.2	C2.3
C2.1	(1, 1, 1)	(2/3, 1,2)	(1, 3/2, 2)
C2.2	(1/2, 1, 3/2)	(1, 1, 1)	(3/2, 2, 5/2)
C2.3	(1/2, 2/3, 1)	(2/5, 1/2, 2/3)	(1, 1, 1)

The normalized weight vector with respect to Environmental Condition is obtained as:

Criterion	C2.1	C2.2	C2.4
W %	39.3%	44.0%	16.7%

B.1.3 Structural Capacity (SC)

Table B. 3: The fuzzy evaluation matrix with respect to Structural Capacity (SC)

	C3.1	C3.2	C3.3	C3.4
C3.1	(1, 1, 1)	(1, 3/2, 2)	(1/2, 2/3,1)	(1, 1, 1)
C3.2	(1/2, 2/3, 1)	(1, 1, 1)	(2/5,1/2,2/3)	(2/3, 1 ,2)
C3.3	(1, 3/2, 2)	(3/2, 2, 5/2)	(1, 1, 1)	(1/2, 1, 3/2)
C3.4	(1, 1, 1)	(1/2, 1, 3/2)	(2/3, 1, 2)	(1, 1, 1)

The normalized weight vector with respect to Structural Capacity is obtained as:

Criterion	C3.1	C3.2	C3.3	C3.3
W %	23.84%	18.51%	33.41%	24.23%

B.1.4 Durability (Du.)

Table B. 4: The fuzzy evaluation matrix with respect to Durability (Du.)

	C4.1	C4.2	C4.3
C4.1	(1,1,1)	(2/3, 1, 2)	(1, 3/2, 2)
C4.2	(1/2, 1, 3/2)	(1,1,1)	(3/2, 2, 5/2)
C4.3	1/2, 2/3, 1)	(2/5, 1/2, 2/3)	(1,1,1)

The normalized weight vector with respect to Durability is obtained as:

Criterion	C4.1	C4.2	C4.3
W %	39.3%	44.1%	16.7%

B.1.5 Professional Involvement (P.I)

Table B. 5: The fuzzy evaluation matrix with respect to Professional Involvement (PI)

	C5.1	C5.2
C5.1	(1,1,1)	(1,1,1)
C5.2	(1,1,1)	(1,1,1)

The normalized weight vector with respect to Professional Involvement is obtained as:

Criterion	C5.1	C5.2
W %	50%	50%

B.2 Pairwise Comparisons of Second Level Sub-Criteria.

B.2.1 Beam (C3.1) and Slab (C3.2)

Table B. 6: The fuzzy evaluation matrix with respect to (C3.1) and (C3.2)

	C3.x.1	C3.x.2	C3.x.3
C3.x.1	(1,1,1)	(1/2, 1, 3/2)	(3/2, 2, 5/2)
C3.x.2	(2/3, 1, 2)	(1,1,1)	(1/2, 1, 3/2)
C3.x.3	(2/5, 1/2, 2/3)	(2/3, 1, 2)	(1,1,1)

The normalized weight vector with respect to (C3.1) and (C3.2) is obtained as:

Criterion	C3.1.1	C3.1.2	C3.1.3
W %	41.2%	32.5%	26.3%

B.2.2 Columns and / or walls (C3.3)

Table B. 7: The fuzzy evaluation matrix with respect to Deflection (C3.3)

	C3.3.1	C3.3.2
C3.3.1	(1,1,1)	(1, 3/2, 2)
C3.3.2	(1/2, 2/3, 1)	(1,1,1)

The normalized weight vector with respect to Deflection is obtained as:

Criterion	C3.3.1	C3.3.2
W %	68.4%	31.6%

B.2.3 Tilting and settlement (C3.4)

Table B. 8: The fuzzy evaluation matrix with respect to Tilting and settlement (C3.4)

	C3.4.1	C3.4.2
C3.4.1	(1,1,1)	(4/7, 4/5, 4/3)*
C3.4.2	(3/4, 5/4, 7/4)	(1,1,1)

*Note: the TFNs are interpolated between moderate and strong TFNs values.

The normalized weight vector with respect to Tilting and settlement is obtained as:

Criterion	C3.3.1	C3.3.2
W %	43.3%	56.7%

B.2.4 Surface Deterioration (C4.1)

Table B. 9: The fuzzy evaluation matrix with respect to Surface Deterioration (C4.1)

	C4.1.1	C4.1.2
C4.1.1	(1,1,1)	(1, 3/2, 2)
C4.1.2	(1/2, 2/3, 1)	(1,1,1)

The normalized weight vector with respect to Surface Deterioration is obtained as:

Criterion	C4.1.1	C4.1.2
W %	68.4%	31.6%

B.2.5 Corrosion State (C4.2)

Table B. 10: The fuzzy evaluation matrix with respect to Corrosion State (C4.2)

	C4.2.1	C4.2.2
C4.2.1	(1,1,1)	(1, 3/2, 2)
C4.2.2	(1/2, 2/3, 1)	(1,1,1)

The normalized weight vector with respect to Corrosion State is obtained as:

Criterion	C4.2.1	C4.2.2
W %	68.4%	31.6%

B.2.6 Finishing Material State (C4.3)

Table B. 11: The fuzzy evaluation matrix with respect to Finishing Material State (C4.3)

	C4.3.1	C4.3.2
C4.3.1	(1,1,1)	(1,1,1)
C4.3.2	(1,1,1)	(1,1,1)

The normalized weight vector with respect to Finishing Material State is obtained as:

Criterion	C4.3.1	C4.3.2
W %	50%	50%