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A GENETIC RULE-BASED FUZZY SYSTEM TO ESTIMATE THE COVER THICKNESS OF DURABLE RC STRUCTURES

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ABSTRACT

The skeptical part of building regulations for durability-design process might be attributed to the ambiguities arising from the qualitative and linguistic definitions of the relevant parameters when dealing with the service life and durability of reinforced concrete (RC) structures. Handling of these parameters with traditional methods is not a straightforward matter but fuzzy systems as an advanced tool for processing the linguistic knowledge could be easily utilized to address this issue. Accordingly this paper introduces a support system assisted by rule-based genetic fuzzy system to quantify the environmental aggressiveness and subsequently infer a minimum cover thickness for durable reinforced concrete members in the corrosive environments.

Keywords: Reinforced concrete; concrete durability; rule-based fuzzy systems; genetic algorithm

1. INTRODUCTION

In most of the national and international building codes and their guides [1-5], the durability provisions for reinforced concrete structures are established based on a set of specifications like minimum grade of concrete, maximum water to cement ratio, cement content, minimum cover to reinforcement and etc. [3-5]. Although this approach is simple and reliable for most environments and common concrete structures, the real service life of the structures designed and constructed under this scheme is not clear and might be ineffective for new materials or different environmental conditions. In fact these regulations are based on the previous experiences of the structural responses to the different environments [3,6]. To improve and relieve of these situations, the concept of service-life design is introduced by researchers of material sciences and structural engineers. Nowadays, some frontier building codes and researchers are trying to develop model codes for service life design. Recently, these cooperative efforts bring out a model code for service life design [7]. Unfortunately there is not a reliable tool for quantifying the environmental effects and there are not

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appropriate methodologies to support the current model codes. In this paper it is intended to introduce a methodology to obviate some of the uncertainties associated with the service-life design regarding the corrosion of reinforcements; in particular, the required cover thickness over the reinforcing bars. To this end, a rule-based fuzzy support system is proposed which is tuned by genetic algorithms to regulate the membership functions of the temperature vector as a tunable variable to the environmental aggressiveness quantifier fuzzy system. Moreover, a fuzzy system is proposed to determine the minimum required cover thickness over the reinforcement which is supported by the aforementioned genetic-fuzzy system.

2. DURABILITY DESIGN OF CONCRETE STRUCTURES

Traditionally the durability design of concrete structures is based on implicit rules for materials, material compositions, working conditions, structural dimensions, etc. Examples of such ‘deem-to-satisfy’ rules are the requirements for minimum concrete cover, maximum water/cement ratio, minimum cement content, crack limitation, air content, cement type and coatings on concrete. These rules are sometimes related to the type of environmental exposure such as indoor climate, wet exposure, presence of frost and deicing salts, sea water and so on. The purpose of all these rules has been to secure robustness for structures, although no clear definition for service life has been presented. Modern building codes will increasingly be based on the performance of buildings. It must be ensured that this performance exists throughout the service life of the building. With deem-to-satisfy rules it is not possible to give an explicit relationship between performance and service life. For concrete, but also for other building materials, these relationships are not yet available as design tools [8].

In this regard, this paper covers one of the most important components of service-life design i.e., the required cover to the reinforcing bar to be as required as possible in each circumstances and environments that is automatically generated and inferred by entering the exposed environment’s temperature, relative humidity, degree of wetting and dying regarding the utilized concrete quality.

3. CORROSION AND SERVICE LIFE DESIGN

Actual period during which no unacceptable expenditure on maintenance or repair required can be an appropriate and simple definition for the service life of concrete structures [6, 9]. Meanwhile, durability is defined as the ability of the building and its parts to retain their performance under the effect of agents over a given period. In this sense, the durability design concepts are introduced to gain these missions and goals.

The corrosion of reinforcement is one of the important factors to be considered in durability- based service life design of reinforced concrete structural members in severe environments. Along with other factors, service life of a structural member with respect to corrosion of reinforcement depends upon the exposure condition and the type and quality of concrete used. As said before, in most of the codes of practice, exposure conditions are classified in a general and qualitative manner [1-3]. Consequently, this leads to the complexities in the qualification and selection process of the exposure condition for a structure or structural member which is required in the durability design procedure. In addition, there are some uncertainties in the actual values of water–cement ratio, grade of concrete, and cover thickness used in the construction. These uncertainties and ambiguities appear due to the use of linguistic terms for specifying the environmental conditions and quality of construction.

4. FUZZY RULE-BASED SYSTEM (FRBS)

The generic structure of a Mamdani FRBS is shown in Figure 1. The *knowledge base* (KB) stores the available knowledge about the problem in the form of fuzzy *"IF- THEN"* rules. The other three components compose the fuzzy inference engine, which by means of the latter rules puts into effect the inference process on the system inputs. The fuzzification interface establishes a mapping between crisp values in the input domain U and fuzzy sets defined on the same universe of discourse. On the other hand, the defuzzification interface realizes the opposite operation by defining a mapping between fuzzy sets defined in the output domain V and crisp values defined in the same universe [10-11].

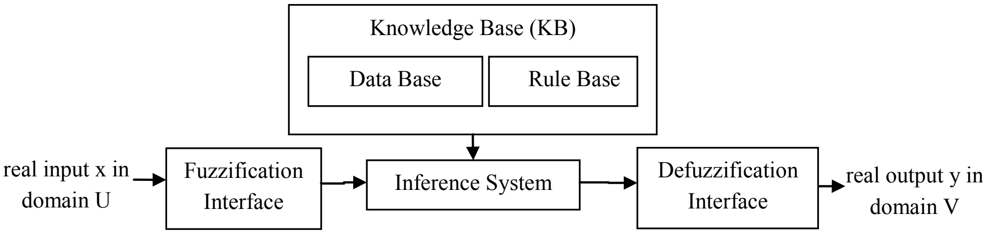


Figure 1. Basic structure of a Mamdani fuzzy rule-based system

5. GENETIC FUZZY RULE-BASED SYSTEMS (GFRBS)

The two main tasks in the FRBS design process are: (1) the design of the inference mechanism, and (2) the generation of the fuzzy rule set (KB or FRB).

One of the major drawbacks of FRBSs is that they are not able to learn, but require the KB to be derived from expert knowledge. The key point is to employ an evolutionary learning process to automate the FRBS design. The automatic definition of an FRBS can be seen as an optimization or search problem, and GAs are a well known and widely used global search technique with the ability to explore a large search space for suitable solutions only requiring a simple scalar performance measure. In addition to its ability to find near optimal solutions in complex search spaces, the generic code structure and independent performance features of GAs make them suitable candidates to incorporate a priori knowledge. In the case of FRBSs, this a priori knowledge may be in the form of linguistic variables, fuzzy membership function parameters, fuzzy rules, number of rules, etc. These capabilities extended the use of GAs in the development of a wide range of approaches for designing FRBSs over the last few years. Figure 2 illustrates this idea. It is important to notice that the genetic learning process aims at designing or optimizing the KB. Consequently, a GFRBS is a design method for FRBSs which incorporates evolutionary techniques to achieve the automatic generation or modification of the entire or part of the KB. From the view point of optimization, the problem of finding an appropriate KB to solve an specific problem, is that of defining a parameterised KB where a set of parameters describes the fuzzy rules and fuzzy membership functions, and obtaining a suitable set of parameter values according to the optimization criterion. The KB parameters constitute the optimization space, the phenotype space, which has to be transformed into a suitable genetic representation, the genotype space. In order for the GA to search the genotype space, it requires some mechanism to generate new variants from the currently existing candidate solutions. The objective of the search process is to maximize or minimize a fitness function that describes the desired behaviour of the system.

In summary, the genetic process is the result of the interaction between the evaluation, selection and creation of genetically encoded candidate solutions, which represent the contents of the KB of an FRBS [10-11].

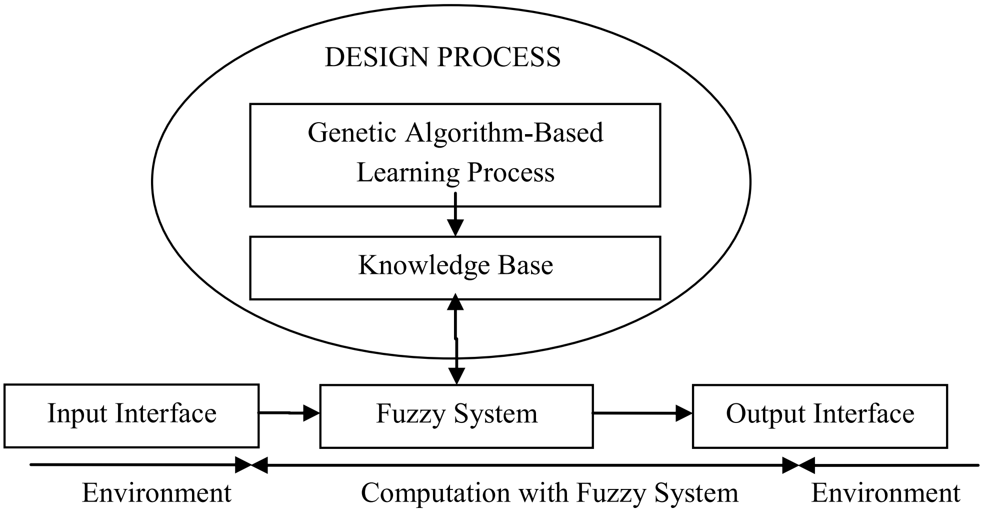


Figure 2. Genetic fuzzy rule-based systems (redrawn from [10])

The remaining part of the paper is devoted to present a rule-based fuzzy system for estimating the required cover thickness over the reinforcements. To address this system, it is required to develop a rule-based genetic-fuzzy system to quantify the aggressions of the environment subjected to the involved parameters.

6. RULE-BASED GENETIC-FUZZY SYSTEM TO ESTIMATE REQUIRED COVER THICKNESS

The proposed rule-based genetic fuzzy system which is employed to determine the cover thickness of durable RC member is composed of two major systems. The first one is a rule-based genetic-fuzzy system named as EQFS designed to determine the quantity of environmental aggressiveness with respect to the temperature, relative humidity and degree of wetting and drying.

The second system named as CDFS, is a pure rule-based fuzzy system which supported by EQFS genetic fuzzy system and receives quantified values of environment aggressiveness in addition to the concrete grade and water to cement ratio to estimate the suitable cover thickness. Table 1 summarizes the main common properties of both mentioned fuzzy systems.

Table 1: Common properties of EQFS and CDFS

Type	And method	Or method	Implication	Aggregation	Defuzzification
Mamdani	min	max	min	max	Centroid

6.1 Fuzzy quantification of environmental aggressiveness

To quantify the aggressiveness of the exposed environment, a fuzzy system named as EQFS is proposed with three input variables and one output as shown in Figure 3. Three inputs including the temperature of environment (T), relative humidity (RH) and degree of wetting and drying (DW). Environmental aggressiveness factor is defined in an arbitrary support range of 0-9 as output element of the EQFS.

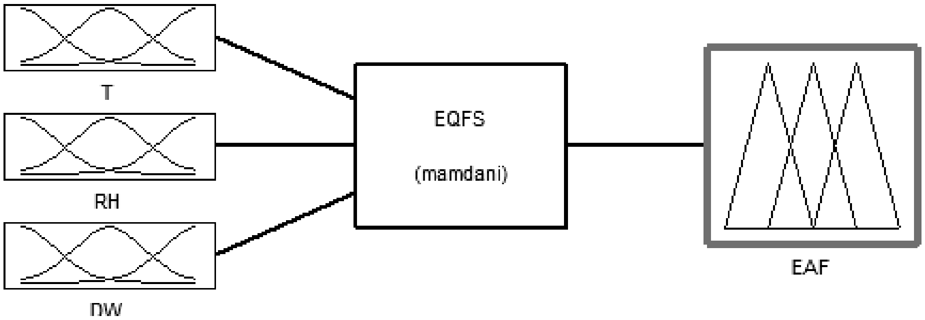


Figure 3. Designed fuzzy system to quantify the environmental aggressiveness factor (EQFS)

Fuzzy membership functions of the input/output variables are represented in Figures 4-7. As it can be seen, the fuzzy decomposition for variable Temperature (T) is left to be variable in its support for Cool, Warm and Hot fuzzy labels. The genetic algorithm (GA) are employed to optimize the support vector of [a, b, c, d] such that the output of the system

(EAF) be in compliance with the regulations of building codes to be mentioned subsequently.

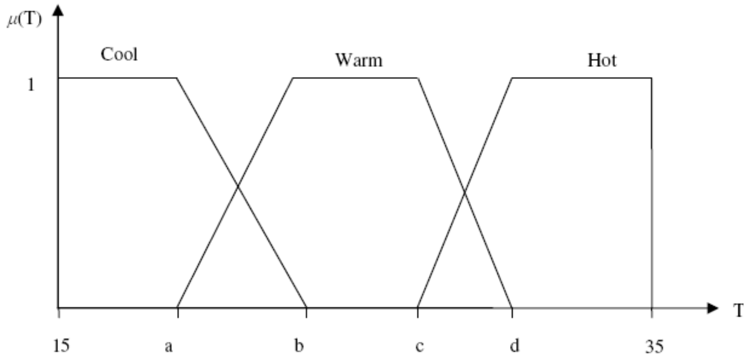


Figure 4. Membership functions for temperature

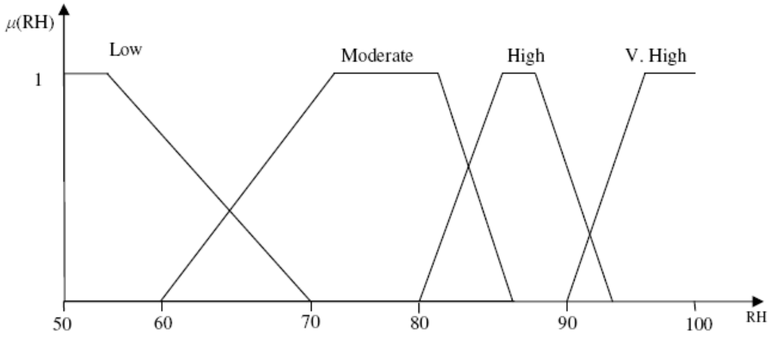


Figure 5. Membership functions for relative humidity

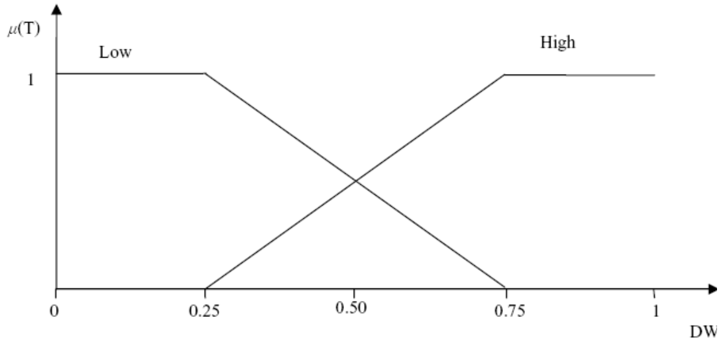


Figure 6. Membership functions for degree of wetting and drying

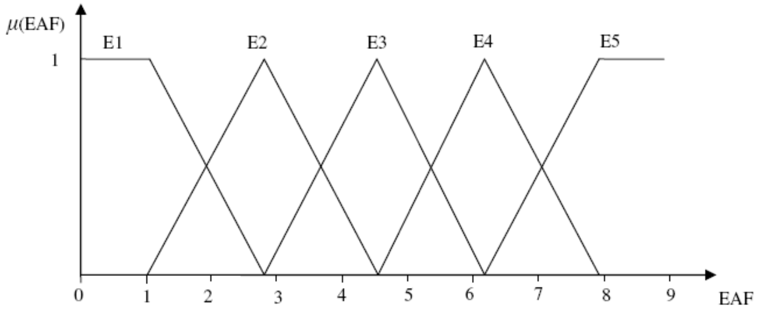
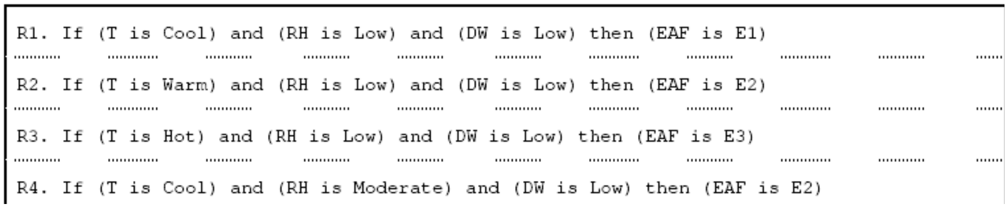


Figure 7. Membership functions for environmental aggressiveness factor

EQFS contains 24 If-Then rules which are heuristically extracted from Eurocode 2 general classifications for exposure as summarized in Table 2. The general format of theses rules are:

<<IF T is --- and RH is --- and DW is --- THEN EAF is ---. >>

Some examples of these rules are demonstrated in Figure 8.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R1. If (T is Cool) and (RH is Low) and (DW is Low) then (EAF is E1)
............ ............ ............ ............ ............ ............ ............ ............ ............ ............ .......
R2. If (T is Warm) and (RH is Low) and (DW is Low) then (EAF is E2)
............ ............ ............ ............ ............ ............ ............ ............ ............ ............ .......
R3. If (T is Hot) and (RH is Low) and (DW is Low) then (EAF is E3)
............ ............ ............ ............ ............ ............ ............ ............ ............ ............ .......
R4. If (T is Cool) and (RH is Moderate) and (DW is Low) then (EAF is E2)
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Figure 8. Examples of rules included in EQFS

Table 2: Classification of exposure conditions

Exposure		**Name**	**Environmental conditions**
1	Moderate	E1	Dry environment
2	Severe	E2a	Humid environment without frost
		E2b	Humid environment with frost
3	Very Severe	E3	Humid environment with frost and de-icing agents
4	Extreme	E4a	Sea-water environment
		E4b	Sea-water environment with frost
5	Aggressive	E5a	Slightly aggressive chemical environment
		E5b	Moderately aggressive chemical environment
		E5c	Highly aggressive chemical environment

6.1.1 Optimization of EQFS with aid of GA

As said before, the Temperature (defined as vector [a, b, c, d]), as one of the input linguistic variables for EQFS fuzzy system is considered to be optimized to fulfill the recommendations of building codes. To optimization purposes, we use GA approach. Following the CEB guide for durability [2], with increasing the temperature from 15 to 25 degree, approximately results in 1.6 times increase in aggressively of environment regarding the concrete cover. This criterion is considered as fitness function of the applied GA modulus. Table 2 summarizes the major configuration for utilized GA.

Table 2: Configuration of GA

Options	**Configuration**
Population type	Double
Population size	20
Population creation function	Uniform
Fitness scaling	Rank
Selection method	Stochastic uniform
Mutation method	Adaptive feasible
Cross over method	Scattered

Table 3: GA optimization for temperature variable belong to EQFS

Run number	**GA Optimization result**	**Mean error**
1	[16.4507 19.9958 22.5243 25.3082]	2.788e-13
2	[16.6272 19.5582 22.2271 25.3452]	4.88e-16
3	[16.0012 21.4436 22.7630 25.2785]	7.40e-14
4	[16.3366 21.5151 23.0121 25.2474]	5.320e-15
Optimized point	[16.6272 19.5582 22.2271 25.3452]	4.880e-16

Results of optimization are summarized in Table 3. As an example case, Figure 8 shows the optimization process for run number 2 which is reached to minimum error of 4.88e-16. Based on the results of Table 3, the final configuration of fuzzy sets for variable

Temperature (T) is reconfigured and depicted in Figure 10.

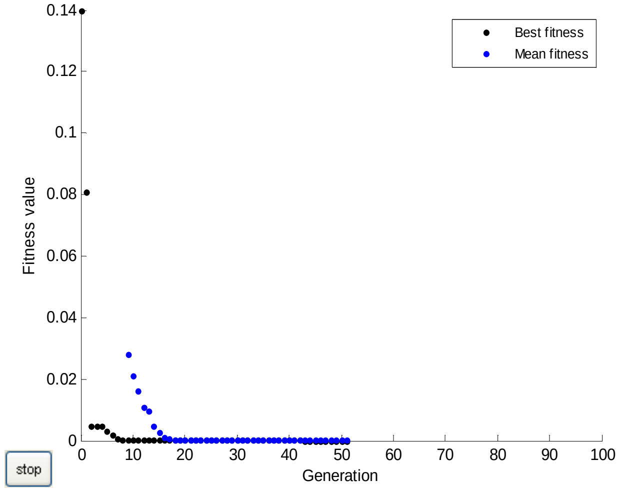


Figure 9. Optimization curve for GA run number 2

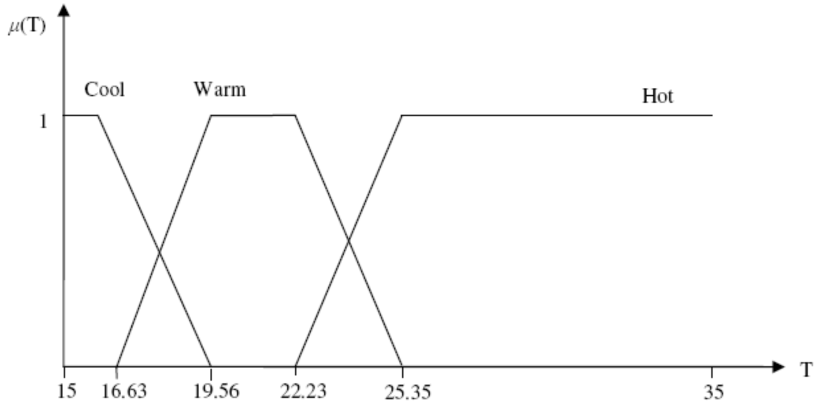
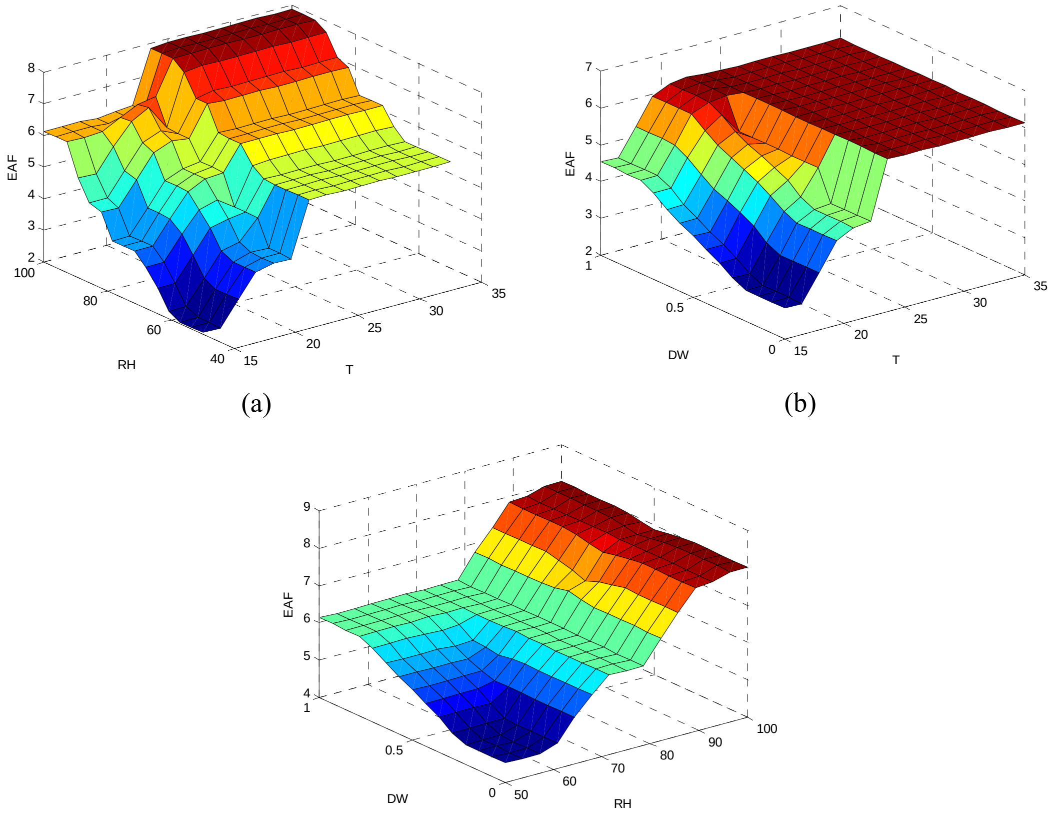


Figure 10. Optimized fuzzy sets for variable temperature of EQFS

6.1.2 Validity study on EQFS

A sensitivity study is carried out to explore the validity of the fuzzy system for EQFS. The results of this study are depicted in Fig .10a to 10-c. These figures show the interaction of T-RH, T-DW, and RH-DW on the values of EAF respectively. It can be seen that by an increase in relative humidity and temperature, the environmental aggressively factor is increased and vice versa, accordingly with a decrease in both mentioned values, the EAF will be decrees accordingly. The maximum value for EAF is found in RH between 50 to 60%, Temperature between 15 to 20^{o}C, however, in RH between 90 to 100% and Temperature greater than 20^{o}C the maximum value of EAF is observed. These observations are all in accordance with CEB guide for durability and thus it can be a confirmation for the validity of the designed fuzzy system for EAF value.



(a) (b)

(c)

Figure 11. Effect of (a) T-RH, (b) T-DW, and (c) RH-DW interactions on EAF values

6.2 Determination of minimum required cover thickness

Based on the CEB durability guide, the minimum required cover thickness (MRCT or MicCov) can be related to the ratio of water to cement (w/c), concrete minimum strength grade (GC) and EAF. In this regard based on Euro code, Tables 4 is organized to select the values of MRCT, maximum w/c with respect to EAF normalized in the intervals of 0-1.8.

Tables 5-8 summarize the requirements proposed by Eurocode 2 to evaluate the MRCT based on EAF and CG. In these tables, nominal Δc_{dev} is the additional deviation. CEB design guide propose to 10 mm based on the applied quality control in construction process. In this paper 10 mm is adopted as a conservative value.

Table 4: Relations of CG, maximum value and w/c ratio

Exposure class	EAF	Maximum w/c	minimum GC*
1	0-1.8	0.65	C20/25
2	1.8-3.6	0.6	C25/30
3	3.6-5.4	0.55	C30/37
4	5.4-7.2	0.55	C30/37
5	7.2-9	0.50	C35/45

*** Ca/b: normal concrete with cylinder (a) cube (b) compressive strength in MPa**

Table 5-a: Minimum required cover thickness for concrete with C20/25 grade

Exposure class	w/c			
	0.5	0.55	0.6	0.65
1	$15+\Delta c_{dev}$*	$15+\Delta c_{dev}$	$15+\Delta c_{dev}$	$15+\Delta c_{dev}$
2	$25+\Delta c_{dev}$	$30+\Delta c_{dev}$	$30+\Delta c_{dev}$	$35+\Delta c_{dev}$
3	$30+\Delta c_{dev}$	$35+\Delta c_{dev}$	$40+\Delta c_{dev}$	$45+\Delta c_{dev}$
4	$50+\Delta c_{dev}$	$50+\Delta c_{dev}$	$55+\Delta c_{dev}$	$60+\Delta c_{dev}$
5	$50+\Delta c_{dev}$	$55+\Delta c_{dev}$	$60+\Delta c_{dev}$	$60+\Delta c_{dev}$

*** corresponding to membership function of cover thickness with label “S15” and the like**

Table 5-b: Minimum required cover thickness for concrete with C25/30 grade

Exposure class	w/c			
	0.5	0.55	0.6	0.65
1	$15+\Delta c_{dev}$	$15+\Delta c_{dev}$	$15+\Delta c_{dev}$	$15+\Delta c_{dev}$
2	$20+\Delta c_{dev}$	$20+\Delta c_{dev}$	$20+\Delta c_{dev}$	$30+\Delta c_{dev}$
3	$30+\Delta c_{dev}$	$30+\Delta c_{dev}$	$35+\Delta c_{dev}$	$40+\Delta c_{dev}$
4	$45+\Delta c_{dev}$	$45+\Delta c_{dev}$	$50+\Delta c_{dev}$	$55+\Delta c_{dev}$
5	$45+\Delta c_{dev}$	$50+\Delta c_{dev}$	$55+\Delta c_{dev}$	$60+\Delta c_{dev}$

Table 5-c: Minimum required cover thickness for concrete with C30/37 grade

Exposure class	**w/c**			
	0.5	**0.55**	**0.6**	**0.65**
1	$15+\Delta c_{dev}$	$15+\Delta c_{dev}$	$15+\Delta c_{dev}$	$15+\Delta c_{dev}$
2	$20+\Delta c_{dev}$	$20+\Delta c_{dev}$	$20+\Delta c_{dev}$	$30+\Delta c_{dev}$
3	$25+\Delta c_{dev}$	$25+\Delta c_{dev}$	$30+\Delta c_{dev}$	$35+\Delta c_{dev}$
4	$40+\Delta c_{dev}$	$40+\Delta c_{dev}$	$45+\Delta c_{dev}$	$50+\Delta c_{dev}$
5	$45+\Delta c_{dev}$	$45+\Delta c_{dev}$	$50+\Delta c_{dev}$	$55+\Delta c_{dev}$

Table 5-d: Minimum required cover thickness for concrete with C35/45 grade

Exposure class	**w/c**			
	0.5	**0.55**	**0.6**	**0.65**
1	$15+\Delta c_{dev}$	$15+\Delta c_{dev}$	$15+\Delta c_{dev}$	$15+\Delta c_{dev}$
2	$20+\Delta c_{dev}$	$20+\Delta c_{dev}$	$20+\Delta c_{dev}$	$25+\Delta c_{dev}$
3	$25+\Delta c_{dev}$	$25+\Delta c_{dev}$	$30+\Delta c_{dev}$	$30+\Delta c_{dev}$
4	$40+\Delta c_{dev}$	$40+\Delta c_{dev}$	$45+\Delta c_{dev}$	$45+\Delta c_{dev}$
5	$40+\Delta c_{dev}$	$45+\Delta c_{dev}$	$45+\Delta c_{dev}$	$50+\Delta c_{dev}$

6.2.1 Cover designer fuzzy system

A fuzzy system named as cover designer fuzzy system (CDFS) is proposed to determine the minimum cover thickness of concrete members as shown in Figure 11.

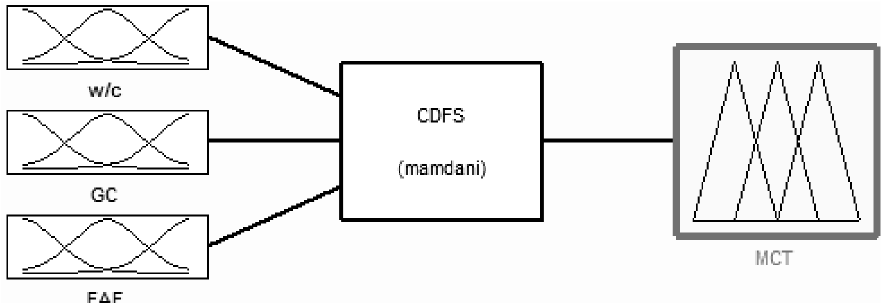


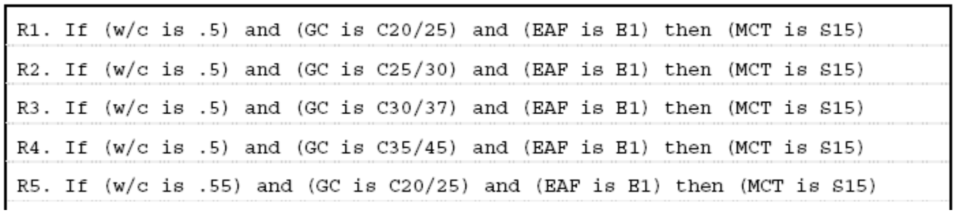
Figure 12. Designed fuzzy system to evaluate the minimum cover thickness (CDFS)

In this system, three inputs including maximum w/c ratio (w/c), grade of concrete (GC) and environmental aggressiveness factor (EAF) and one output, i.e. minimum cover thickness (MRCT) are considered. It should be noted that the core of CDFS fuzzy system is similar to EQFS fuzzy system.

80 If-Then rules are specified for CDFS which heuristically extracted from the Eurocode rules of thumb summarized in Tables 4 and 5a-d. The general format of theses rules are:

IF w/c is --- and GC is --- and EAF is --- THEN MCT is ---.

Examples of these rules are shown in Figure 12. Moreover, the fuzzy membership functions of input and output variables are represented in Figures. 14-16.



R1. If (w/c is .5) and (GC is C20/25) and (EAF is B1) then (MCT is S15)

R2. If (w/c is .5) and (GC is C25/30) and (EAF is B1) then (MCT is S15)

R3. If (w/c is .5) and (GC is C30/37) and (EAF is B1) then (MCT is S15)

R4. If (w/c is .5) and (GC is C35/45) and (EAF is B1) then (MCT is S15)

R5. If (w/c is .55) and (GC is C20/25) and (EAF is B1) then (MCT is S15)

Figure 13. Examples of rules employed in CDFS

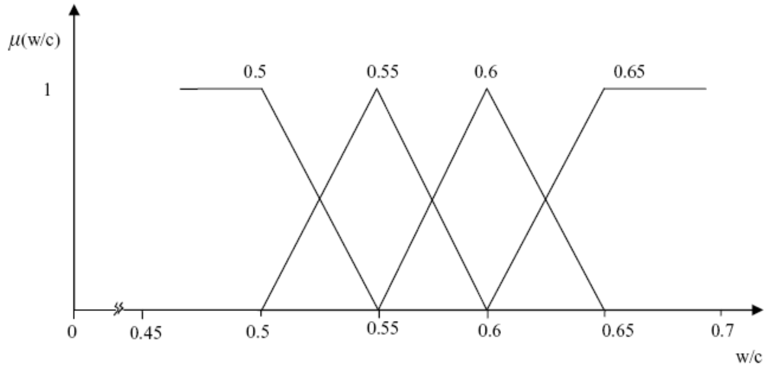


Figure 14. Membership functions for w/c

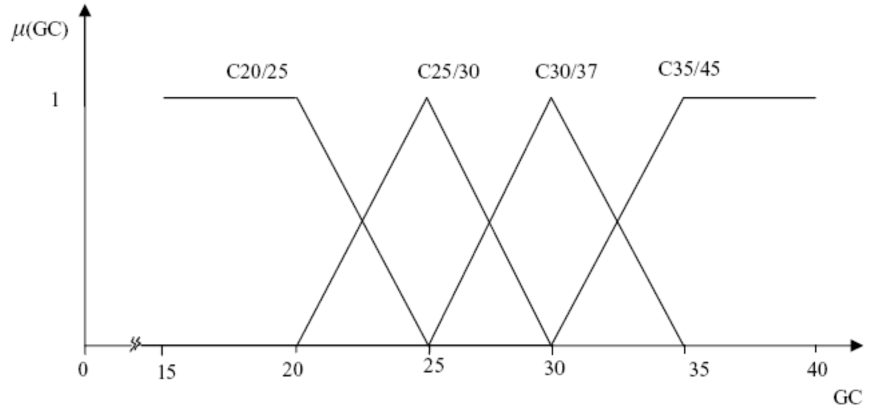


Figure 15. Membership functions for CG

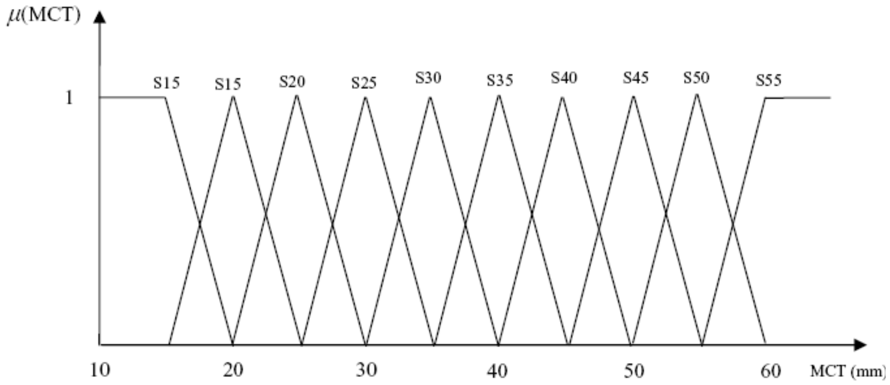
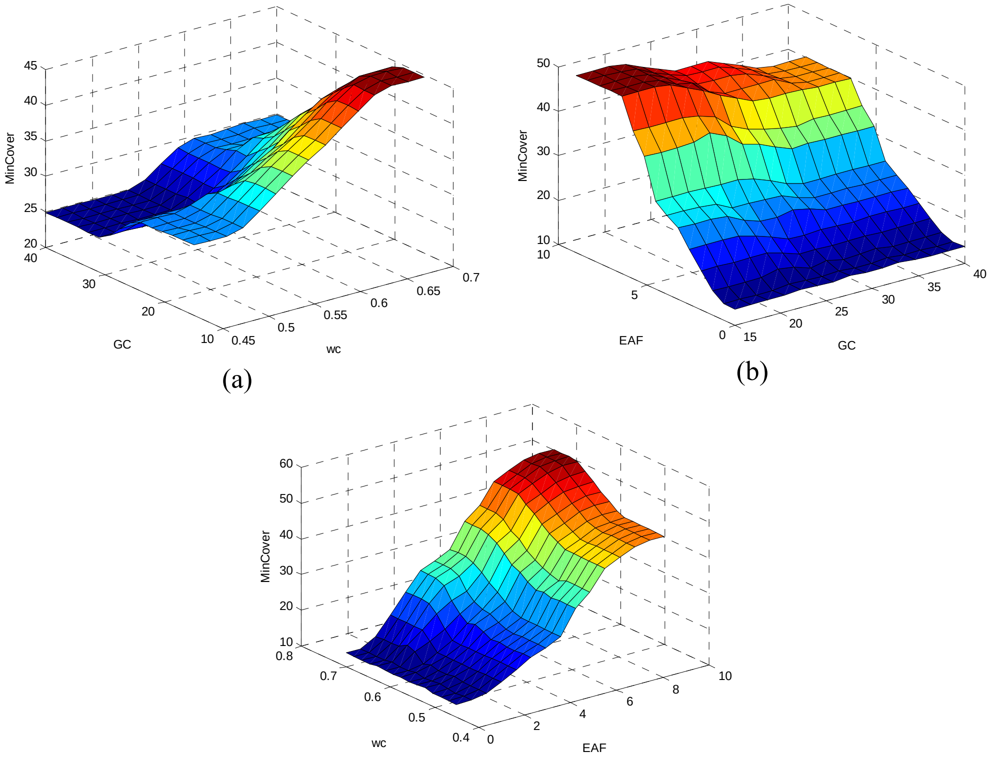


Figure 16. Membership functions for MCT

Figures 17a-17c show the reciprocal influence of CG, maximum w/c and EAF on the minimum required cover thickness as spatial surfaces. Using these surfaces and CDFS, a sensitivity analysis has been carried out on the mutual effect of CG and EAF value on the minimum required cover thickness. Figure 18 shows the effect of environmental aggressiveness on the required cover thickness is depicted for increasing amount of w/c ratio. This figure demonstrates that increasing the value of EAF would leads to increase in the cover thickness. Irrespective of the aggressiveness of environment and grade of concrete, CEB design guide gives an increase of 1.5 times in the cover factor when the w/c ratio is increased from 0.50 to 0.60. Sensitivity study on the proposed CDFS system (Figure 19) shows that when increasing the w/c ratio from 0.5 to 0.6, minimum required cover thickness is increased by 1.32 times which is comparable to the CEB design guide value. As a result it can be said that the designed fuzzy system are fairly valid as a tool for calculating the required cover thickness in different environment and different concrete quality.



(a) (b)

(c)

Figure 17. Reciprocal influence of (a) CG-maximum w/c, (b) EAF-GC and maximum w/c-EAF on the minimum required cover thickness

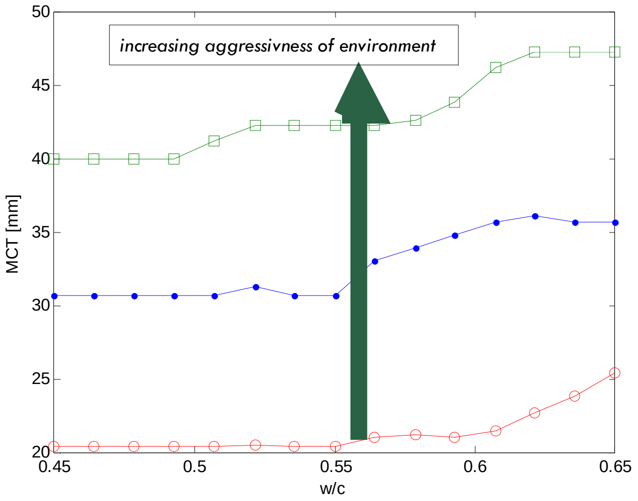


Figure 18. Effect of EAF on the cover thickness with increasing the ratio of w/c

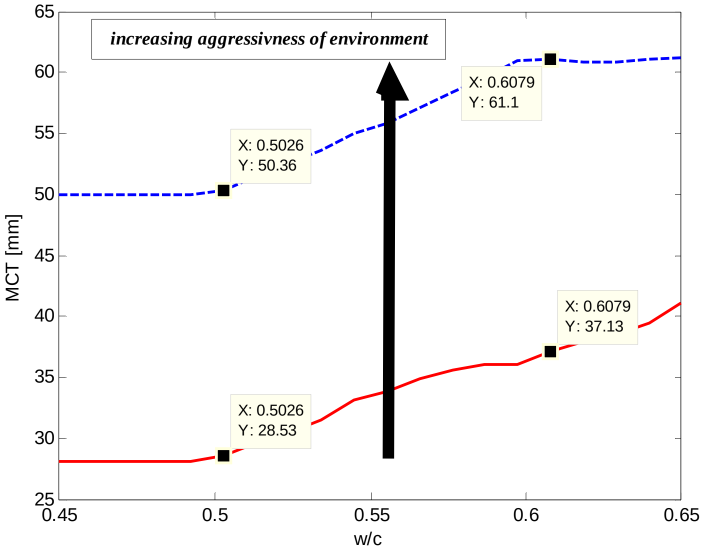


Figure 19. Sensitivity analysis effect of w/c on the required cover thickness

7. SUMMERY AND CONCLUDING REMARKS

To reach durability requirements and avoid the concise service life of concrete structure, it is needed to consider some crucial matters in the designing process. In particular, the cover thickness as the dominant element of the durability is well-treated in the building codes. Unfortunately, there is not an established methodology to aid the designers to make a reliable decision regarding the amount of the cover thickness based on the exposure condition, type of utilized concrete, quality and etc. This paper introduced a reliable methodology based on the fuzzy systems and genetic algorithm to resolve these difficulties. In this paper a fuzzy system named as CDFS was proposed to estimate the cover thickness of reinforced concrete structures which supported by a genetic-fuzzy rule-based system named as EQFS. Using the proposed system, the interaction effects of involved parameters including the temperature, relative humidity, concrete grade and water to cement ration on the cover thickness were studied and utilized to verify by recommendations of building codes. With aid of the developed system, structural engineers could be design durable concrete structures with optimized cover thickness.

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