APPLICATION OF FUZZY SET THEORY IN FACILITIES LAYOUT PLANNING
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>LIST OF FIGURES</td>
<td>iii</td>
</tr>
<tr>
<td>LIST OF TABLES</td>
<td>v</td>
</tr>
<tr>
<td>ABSTRACT</td>
<td>1</td>
</tr>
<tr>
<td>INTRODUCTION</td>
<td>2</td>
</tr>
<tr>
<td>INTRODUCTION TO FUZZY SET THEORY</td>
<td>3</td>
</tr>
<tr>
<td>Fuzzy Sets</td>
<td>3</td>
</tr>
<tr>
<td>Fuzzy Set Operations</td>
<td>4</td>
</tr>
<tr>
<td>Fuzzy Linguistic Variables</td>
<td>5</td>
</tr>
<tr>
<td>Fuzzy Control and Fuzzy Decision-Making System</td>
<td>5</td>
</tr>
<tr>
<td>INTRODUCTION TO GENETIC ALGORITHM</td>
<td>7</td>
</tr>
<tr>
<td>LITERATURE REVIEW OF RELATED EFFORTS</td>
<td>9</td>
</tr>
<tr>
<td>THE PROPOSED APPROACH</td>
<td>10</td>
</tr>
<tr>
<td>Generating the Weight Factors</td>
<td>13</td>
</tr>
<tr>
<td>Establishing the IF-THEN decision rules</td>
<td>14</td>
</tr>
<tr>
<td>Developing a Program for the Inference of the Decision Rules to Generate the Facility Relationship Chart (FRC)</td>
<td>15</td>
</tr>
<tr>
<td>Developing the Physical Layout of Facilities</td>
<td>21</td>
</tr>
<tr>
<td>Evaluating the Generated Layouts</td>
<td>24</td>
</tr>
<tr>
<td>COMMENTS AND DISCUSSION</td>
<td>25</td>
</tr>
<tr>
<td>CONCLUSION</td>
<td>26</td>
</tr>
<tr>
<td>REFERENCES</td>
<td>27</td>
</tr>
</tbody>
</table>
APPENDICES  ........................................................................................................... 30

Appendix A: The Weight Factors Between Each Pair of Facilities ........ 30
Appendix B: Decision Rules ............................................................... 33
Appendix C: Visual Basic Program Listing ........................................ 36
Appendix D: The Max-Min Firing Rules for Facilities 2 and 4 ............ 48
Appendix E: The Overall Membership Functions ............................. 63
Appendix F: Solutions Generated by Genetic Algorithms ............... 67
LIST OF FIGURES

Fig. 1: The union of the fuzzy sets $\tilde{A}$ and $\tilde{O}$ ...................................... 4
Fig. 2: The intersection of the fuzzy sets $\tilde{A}$ and $\tilde{O}$ .............................. 4
Fig. 3: Membership functions of the temperature linguistic variable .......... 5
Fig. 4: Basic configuration of fuzzy decision-making system .................. 6
Fig. 5: Crossover in strings ................................................................................. 8
Fig. 6: Membership functions of material flow (MF) ................................. 11
Fig. 7: Membership functions of information flow (IF) ............................ 12
Fig. 8: Membership functions of equipment flow (EF) ............................. 12
Fig. 9: Membership functions of closeness rating (R) ............................... 12
Fig. 10: Membership functions of weight factor (WF) .............................. 14
Fig. 11: IF-THEN rules of (a) material flow (MF) and its weight factor (WF); (b) information flow (IF) and its weight factor; and equipment flow (EF) and its weight factor .............................................................. 15
Fig. 12: The part of the visual basic program used to perform the max-min rule of inference .......................................................... 16
Fig. 13: (a) Number of input variables; (b) number of membership functions for the material flow .......................................................... 17
Fig. 14: Values of the second membership function (low) for the material flow ... 17
Fig. 15: The input value of the first variable (MF) between facilities 2 and 4 ....... 18
Fig. 16: The input value of the second variable (WF) of (MF) between facilities 2 and 4 ............................................................. 18
Fig. 17: The total number of rules between (MF) and its (WF) ..................... 18
Fig. 18: The membership functions of each variable in rule number 1 .......... 19
Fig. 19: The fuzzy inference and defuzzification methods .......................... 19

Fig. 20: Overall membership functions of facilities (2-4) for material flow, information flow, and equipment flow .......................... 20

Fig. 21: Facility relationship chart .......................................................... 21

Fig. 22: The user interface of the genetic algorithm program ...................... 21

Fig. 23: Distance between facilities .......................................................... 23

Fig. 24: The selected population size .......................................................... 23

Fig. 25: The selected number of generations per cycle .............................. 24

Fig. 26: The selected layout ........................................................................ 25
LIST OF TABLES

Table 1. Relationships and intensity importance of factors among all facilities ................................................................. 13
Table 2. The weight factors between facilities 1 & 3 ($a_{ij}$) ................................................................. 14
Table 3. The average closeness rating values ................................................................. 20
Table 4. Required inputs for each facility ................................................................. 22
APPLICATION OF FUZZY SET THEORY IN FACILITIES LAYOUT PLANNING

ABSTRACT

The layout of temporary facilities in a construction site deals with the selection of the most efficient layout of these facilities in order to operate efficiently and cost effectively. The layout design seeks the best arrangement of facilities within the available area. In the design process of the layout, many objectives must be considered to effectively utilize people, equipment, space, and energy. This project, therefore, proposes a methodology based on the fuzzy set theory and genetic algorithm technique to improve the layout process of facilities. The main objective of this study is to obtain the closeness rating values between each two facilities in the construction site. To achieve this objective, the fuzzy set theory and genetic algorithms technique were used to investigate the layout of temporary facilities in relation with the building(s) to be built in a construction site. An example application was presented to illustrate the proposed approach and the results were then discussed. In this example, it was assumed that the construction site consists of five temporary facilities. It is also considered that three fuzzy input factors (linguistic variables) will affect the layout process. Each of these variables will have five fuzzy sets ranging from very low to very high.

Based on the above assumptions, a visual basic spreadsheet program was written for the fuzzification of the input variables, the fuzzy inference, and the defuzzification of the overall output membership functions. Initially, the fuzzification of the input variables was performed. Afterwards, the minimum operator (max-min composition rule of inference) was used and finally, the defuzzification process was applied using the centroid of the area method to convert the fuzzy output into a crisp value. The final crisp values (closeness ratings) represent the importance of the relationships between each two facilities. Using a genetic algorithm program, these values were then entered to the program along with the facilities and site areas to generate the best possible layout for these facilities in the site. Depending on the importance of relationships among the various facilities in a construction site, this study is expected to provide engineers with an appropriate tool to compare and evaluate different layouts and select the most appropriate and efficient one.
INTRODUCTION

The layout problem is one of the most crucial problems in the planning of service facilities, since efficient layout is critical to cost-effective operation of these facilities. Also, site space is a resource that is as important as money, time, material, labor and equipment. Despite of its importance, site planning is often neglected and the attitude of engineers has been that it will be done as the project progresses. Good facility layout, however, is important to promote safe and efficient operations, minimize travel time, decrease material handling, and avoid obstructing material and equipment movements (Tommelein et al. 1992). In the design process of the layout, therefore, many objectives must be considered to effectively utilize people, equipment, space, and energy (Tomkins and White 1984). Traditionally, in planning a layout the architect starts by making a layout diagram for the facility(ies). This diagram normally consists of different activities connected to each other. The design then proceeds by trial and error until a compromise is reached which more or less satisfies all the known factors and restrictions (Whitehead and Eldars 1965). As such, a layout is traditionally developed using relationships among the various facilities. These relationships are based on the judgement of experts that decide the importance of such relationships between each pair of facilities, which ranges from absolutely necessary to undesirable. The decision of experts, however, is vague and usually based on many quantitative or qualitative considerations for the desired closeness, or closeness relationships among the facilities. The flow of materials between facilities and the ease of supervision of employees are examples of such vague issues. Quantitative methods consider the actual transportation cost per unit time or the amount of materials moved per unit time between each two locations (Zouein 1995). Qualitative methods, on the other hand, consider a subjective numerical proximity weight to express the desirability of having any two facilities close to each other on the layout. Both methods are used in this study.

In an effort to improve the layout process of facilities, this project investigates the layout of temporary facilities in a construction site in relation with the building(s) to be constructed using the fuzzy set theory (Zadeh 1965; Zadeh 1973) and genetic algorithms technique. An example application was presented to demonstrate the proposed approach and the results were then discussed. It was assumed that the construction site consists of five temporary facilities: offices, warehouse (storage), batch plant, maintenance workshop, and quality control laboratories. It is also considered that three fuzzy input factors (linguistic variables) will affect the decision of the planner of the site. These variables are: 1) material flow (MF); 2) information flow (IF); and 3) equipment flow (EF). Each of these variables will have five fuzzy sets {very low (VL), low (L), medium (M), high (H), and very high (VH)}. A visual basic spreadsheet program was developed for the fuzzification of the input variables, the fuzzy inference, and the defuzzification process. After the fuzzification of the input variables was performed, the minimum operator (Mamdani and Assilian 1975; Mamdani 1976) was used and the defuzzification
process was applied using the centroid of the area (COA) method to convert the fuzzy output into a crisp value. The final crisp values represent the closeness rating between each two facilities. These values were used to generate the best layout for the temporary facilities in the construction site using a genetic algorithm program. An introduction about the fuzzy set theory and genetic algorithms was first presented. The approach was explained on an application example to demonstrate its validation. The results along with the best layout obtained by the genetic algorithm technique were then presented and the advantages and drawbacks of the proposed technique were then discussed.

INTRODUCTION TO FUZZY SET THEORY

The real world is complex; complexity in the world generally arises from uncertainty in the form of ambiguity. Problems featuring complexity and ambiguity have been addressed subconsciously by humans since they could think; these ubiquitous features pervade most social, technical, and economic problems faced by the human race. The fuzzy set theory was, therefore, introduced by Zadeh (1965) to deal with vague, imprecise, and uncertain problems. Fuzzy set theory has been used as a modelling tool for complex systems that are hard to define precisely, but can be controlled and operated by humans. Humans can make decisions in the absence of clearly defined boundaries based on expertise and general knowledge of the task of the system in consideration. The humans’ actions are based on the IF-THEN rules they develop over years of knowledge and experience.

Fuzzy Sets

A fuzzy set is a set containing elements that have varying degrees of membership in the set. Unlike the classical, or crisp, sets because members of crisp set would not be members unless their membership was full in that set (i.e., their membership is assigned a value of 1). Elements of a fuzzy set are mapped to a universe of membership value using a function-theoretic form. This function maps elements of a fuzzy set, will be denoted by $\tilde{A}$, to a real numbered value on the interval 0 to 1.

A notation of convention for fuzzy sets when the universe of discourse $X$, is discrete and finite is:

$$\tilde{A} = \left\{ \frac{\mu_2(x_1)}{x_1} + \frac{\mu_2(x_2)}{x_2} + \cdots \right\}$$

When the universe, $X$, is continuous and infinite:

$$\tilde{A} = \left\{ \int_{x_1}^{x_2} \mu_2(x_1) \right\}$$
In both notations, the horizontal bar is not a quotient but rather a delimiter. The numerator is the membership value in set \( \tilde{A} \) associated with the element of the universe indicated in the denominator. The + signs in the first notation is not the algebraic "add" but are a function-theoretic union. The integral sign in the second notation is not an algebraic integral but a continuous function-theoretic union for continuous variables.

Fuzzy Set Operations

There are three basic operations that can be applied to fuzzy sets: union, intersection, and complement. Assume \( \tilde{A}, \tilde{O}, \) and \( \tilde{N} \) are fuzzy sets in \( U \) with the membership functions \( \mu_{\tilde{A}}(u), \mu_{\tilde{O}}(u) \) and \( \mu_{\tilde{N}}(u) \), respectively, and \( \tilde{N} \) equals the union of \( \tilde{A} \) and \( \tilde{O} \), then:

\[
\tilde{N} = \tilde{A} \cup \tilde{O} \quad \text{and} \quad \mu_{\tilde{N}}(u) = \mu_{\tilde{A}}(u) \vee \mu_{\tilde{O}}(u) \quad \forall u \in U, \text{ where } \vee \text{ is the maximum as illustrated in Fig. 1 below.}
\]

Fig. 1: The union of the fuzzy sets \( \tilde{A} \) and \( \tilde{O} \) (\( \tilde{N} = \tilde{A} \cup \tilde{O} \)).

Assuming \( \tilde{N} \) equals the intersection of \( \tilde{A} \) and \( \tilde{O} \), then:

\[
\tilde{N} = \tilde{A} \cap \tilde{O} \quad \text{and} \quad \mu_{\tilde{N}}(u) = \mu_{\tilde{A}}(u) \wedge \mu_{\tilde{O}}(u) \quad \forall u \in U, \text{ where } \wedge \text{ is the minimum as shown in Fig. 2.}
\]

Fig. 2: The intersection of the fuzzy sets \( \tilde{A} \) and \( \tilde{O} \) (\( \tilde{N} = \tilde{A} \cap \tilde{O} \)).
For example, if \( U = \{1, 2, 3, 4, 5, 6, 7\}, \ \tilde{A} = \{0.8/3+1/5+0.6/6\}, \ \text{and} \ \tilde{O} = \{0.7/3+1/4+0.5/6\}, \) then 
\[ \tilde{N} = \tilde{A} \cup \tilde{O} = \{0.8/3+1/4+1/5+0.6/6\}, \ \text{and} \ \tilde{N} = \tilde{A} \cap \tilde{O} = \{0.7/3+0.5/6\}. \]

Other fuzzy set operations and properties are explained in Lin and Lee (1996).

**Fuzzy Linguistic Variables**

Linguistic variables take on values that are words in natural language, while numerical variables use numbers as values. Since words are usually less precise than numbers, linguistic variables provide a method to characterize complex systems that are ill-defined to be described in traditional quantitative terms (Zadeh 1975). A linguistic variable is defined by the name of the variable \( x \) and the set term \( T(x) \) of the linguistic values of \( x \) with each value being a fuzzy number defined on \( U \). For example, if temperature is a linguistic variable, then its term set \( T(\text{temperature}) = \{\text{high, medium, low, . . . .}\} \), where each term is characterized by a fuzzy set in a universe of discourse \( U = [0,100] \), as shown in Fig. 3 (Dweiri and Meier 1996). The figure shows that 70\(^\circ\)C belongs to the linguistic variables \{high, medium, and low\} with membership values of \{0.33,0.67,0\}, respectively. Using the maximum value to find the fuzzy set (label) that this temperature value belongs to, 70\(^\circ\)C belongs to the fuzzy set medium with a membership value of 0.67.

![Fig. 3: Membership functions of the temperature linguistic variable.](image)

**Fuzzy Control and Fuzzy Decision-Making System**

Fuzzy set theory is very useful in modelling complex and vague systems. It depicts the control actions of the operators when they can only describe their actions using natural language. Fuzzy set theory is a tool that transforms this linguistic control strategy into a mathematical control method. Fuzzy control was first used
Fuzzy decision-making system (FDMS) consists of four principal components as shown in Fig. 4 (Dweiri and Meier 1996). These four parts are:

1. The fuzzification interface: measures the values of the input and output variables, transfers the range of these values into a corresponding universe of discourse, and converts them into natural language (high, low, very low, etc.).

2. The knowledge base: a database that contains the experts' knowledge of the application and the control rules of the process. The membership functions are decided by the experts based on their knowledge of the system. The fuzzification process is defined at this point.

3. The decision-making logic (decision rules): simulates the experts' decision-making ability based on a fuzzy concept. The connective 'AND' is implemented as a fuzzy conjunction in a cartesian product space in which the input variables take in their respective universe of discourses. The Minimum operator (Mamdani and Assilian 1975; Mamdani 1976) will be used. These rules are in the form of IF-THEN. The membership value of the control action of each rule is the minimum value of the input variables' membership values.

$$\mu_{controlAction} = \text{Min} \{\mu_{label_{Input1}(value)} , \ldots , \mu_{label_{Inputv}(value)}\}$$

Assuming all variables have the same number of membership functions, the number of rules used in controlling the system using fuzzy control is represented by: $$R = (m)^v$$, Where:

- R= number of rules, m= number of membership functions, and v= number of input variables.
Genetic algorithms use the concept of Darwin's theory of evolution to search for solutions for problems in a more "natural" way. Darwin's theory stressed the fact that the existence of all living things is based on the rule of "survival of the fittest." Darwin also postulated that new breeds or classes of living things come into existence through the processes of reproduction, crossover, and mutation among existing organisms (Forrest, 1993).

First, different possible solutions to a problem are created. These solutions are then tested for their performance (i.e., how good a solution they provide). Among all possible solutions, a fraction of the good solutions is selected, and the others are eliminated (survival of the fittest). The selected solutions undergo the processes of reproduction, crossover, and mutation to create a new generation of possible solutions (which are expected to perform better than the previous generation). This process of production of a new generation and its evaluation is repeated until there is convergence within a generation. The benefit of this technique is that it searches for a solution from a broad spectrum of possible solutions, rather than restrict the search to a narrow domain where results would be normally expected. Genetic algorithms try to perform an intelligent search for a solution from a nearly infinite number of possible solutions (Ross 1996).

All genetic algorithms contain three basic operators: reproduction, crossover, and mutation, where all three analogous to their namesakes. Let us consider the overall process of a genetic algorithm before trying to understand the basic processes. First, an initial population of \( n \) strings (for \( n \) parameters) of length \( L \) (the number of bits in each string) is created. The strings are created in a random fashion, i.e., the values of the parameters that are coded in the strings are random values (created by randomly placing the 0s and 1s in the strings). Each of the strings is decoded into a set of parameters that it represents. This set of parameters is passed through a numerical model (fitness function) of the problem space. The numerical model gives out a solution based on the input set of parameters. Based on the quality of this solution, the string is assigned a fitness value. The fitness values are determined for each string in the entire population of strings. With these fitness values, the three genetic operators are used to create a new generation of strings, which is expected to perform better than the previous generations (better fitness values). The new set of strings is again decoded and evaluated, and a new generation is created using the three basic operators. This process is continued until convergence is achieved within a population.

Among the three genetic operators, reproduction is the process by which strings with better fitness values receive correspondingly better copies in the new generation, i.e. we try to ensure that better solutions persist and contribute to better offsprings (new strings) during successive generations. This is a way of
ensuring the "survival of the fittest" strings. Because the total number of strings in each generation is kept a constant (for computational economy and efficiency), strings with lower fitness values are eliminated.

The second operator, crossover, is the process in which the strings are able to mix and match their desirable qualities in a random fashion. After reproduction, crossover proceeds in three simple steps. First, two new strings are selected at random (Fig. 5(a)). Second, a random location in both strings is selected (Fig. 5(b)). Third, the portions of the strings to the right of the randomly selected location in the two strings are exchanged (Fig. 5(c)). In this way information is exchanged and combined. Reproduction and crossover together give genetic algorithms most of their searching power.

The third genetic operator, mutation, helps to increase the searching power. In order to understand the need for mutation, let us consider the case where reproduction of crossover may not be able to find an optimum solution to a problem. During the creation of a generation it is possible that the entire population of strings is missing a vital bit of information (e.g., none of the strings has a 1 at the fourth location) that is important for determining the correct or the most nearly optimum solution. Future generations that would be created using reproduction and crossover would be able to alleviate this problem. Here mutation becomes important. Occasionally, the value at a certain string location is changed, i.e., if there is a 1 originally at a location in the bit string, it is changed to a 0, or vice versa. Mutation thus ensures that the vital bit of information is introduced into generation. Mutation, as it does in nature, takes place very rarely, on the order of once in a thousand bit string locations (a suggested mutation rate is 0.005/bit/generation (Forrest, 1993).
LITERATURE REVIEW OF RELATED EFFORTS

Various efforts have been described in the literature to deal with the site layout problem. To describe these efforts, it is important to look at several dimensions such as the tightly versus loosely packed arrangement of facilities within the site and the optimization versus heuristic approach used to solve the problem. The effort done by Cheng (1992), for example, proposes a loosely-packed solution to the layout problem using a knowledge-based system. Loosely-packed arrangement of facilities, as opposed to tightly-packed, refers to the situation when spaces are permitted between facilities. Loosely-packed arrangement, therefore, is most suitable for construction sites. Also, heuristic, as opposed to optimum solutions, refers to near-optimum solutions that are based on experience and simplified approaches. Due to the complexity of the problem, mathematical optimization was only successful for a single or very limited number of facilities (Rodriguez-Ramos and Francis 1983; Tommelein et al. 1992). This has contributed to the development of various efforts that use non-traditional techniques based on Artificial Intelligence and also to the wide use of heuristic approaches. The use of Artificial Neural Networks, for example, was proposed by Yeh (1995) to optimize a pre-determined site layout. The model minimizes a total cost function that includes the cost of constructing a facility at the assigned location on site and the cost of interacting with other facilities. The majority of researchers, however, have used heuristic approaches and knowledge-based systems to layout the facilities on a construction site in a loosely-packed manner. CONSITE (Hamiani 1987), for example, arranges facilities according to their importance and identifies their possible positions on the site. Then, it applies rule-based constraints to find the final position of each facility. Another model, SIGHTPLAN (Tommelein 1989; Tommelein et al. 1991, 1992) places temporary facilities on a construction site, one at a time, through a constraint satisfaction search.

Dealing with the layout problem from different perspectives, many other researchers are also presented in the literature. The automated layout design program (ALDEP), for example, starts by selecting the first facility at random and places it starting from a given point that represents the top-left corner of the site (Seehof and Evans 1967). The next facility to be placed is the one that has the highest closeness relationship with the first facility. After placing all facilities one after the other, ALDEP uses an objective function to assign a score to the layout and then repeats the process to construct a different layout until user satisfaction. Another model, CORELAP (computerized relationship layout planning), selects the first facility to be the one with highest closeness relationship to all others (Lee and Moore 1967). Next facility to be placed is the one with highest relationship with first selected facility. In case of a tie, the facility with higher relationship to all others is selected and the procedure continues until the layout is completed. A third model, CRAFT (computer relative allocation of facilities techniques) begins with a user
provided layout and uses a more detailed method of calculating the desired
closeness relationship between facilities by considering distances, travel cost, and
material flow between facilities (Armour et al. 1964; Francis and White 1974). It
then make a pair-wise location interchange of facilities which are either adjacent or
have equal areas, until the layout cost can not be reduced further. In addition to
the three basic models, various researchers have developed other models based
primarily on these formulations such as (Rodriguez-Ramos 1982, Malakooti 1987,
and Yeh 1995).

Most of these efforts, however, use some simplified assumptions and do not
consider the vagueness and natural language that humans use to control complex
systems such as facilities planning. On the other hand, they use only a rectangular
site shape and rectangular facilities with a specific aspect ratio. A facility, as such,
is dealt with mainly as one block and not as a group of unit areas that can take
different shapes, as being dealt with in tightly-packed arrangements. This greatly
limits the possible locations in which the facility could be placed within the site.
Also, heuristic and knowledge-based approaches are not guaranteed to provide
optimum solutions and usually do not include an objective function to evaluate
alternative layout solutions. In an attempt to overcome these limitations, this
project presents a powerful methodology, based on the fuzzy set theory, to
improve the facilities layout process using genetic algorithms layout optimization
mechanism. Details of the proposed methodology are described and an example
application is then used to validate the approach.

THE PROPOSED APPROACH

The layout problem is complex and vague. It seeks the best arrangement based
on the desired closeness relationships among the facilities. These relationships
are generated by the designers based on a number of factors. The larger the
number of facilities in a site and the number of factors affecting the design, the
more complex the layout problem becomes. The approach proposed in this study
consists of the following main steps:

1) Generating the weight factors (WF) for all variables between each pair of
facilities. This is achieved using all possible factors that are believed to affect
the layout.
2) Establishing the IF-THEN decision rules.
3) Developing a program for the inference of the decision rules established in the
previous step to generate the facility relationship chart (FRC). This program
was used to perform the fuzzification, fuzzy inference, and defuzzification. The
final crisp values obtained by the defuzzification process were then used to
generate the facility relationship chart.
4) Developing the physical layout of the facilities in the construction site using the
generated facility relationship chart and a genetic algorithm program.
5) Evaluating the different layouts generated by the genetic algorithm program
using the judgement of the human expert.

These steps were applied to an example application. In this example, it was
considered that the construction site consists of five temporary facilities in addition
to the building(s) to be constructed. These facilities are:

1) Offices, with an area of 160 square meters.
2) Warehouse (storage), with an area of 240 square meters.
3) Batch plant, with an area of 500 square meters.
4) Maintenance workshop, with an area of 120 square meters.
5) Quality control laboratories, with an area of 60 square meters.
6) The buildings to be constructed, which consists of two attached buildings with a
total area of 2880 square meters.

As shown in Table 1, the construction site has n*(n-1)/2=6*(6-1)/2=15 relationships
among all facilities, where n is the number of facilities in the site. Let us now
assume that there are three factors (input variables) affecting the decision of the
planner. These factors are:

1) Material flow (MF): defined by the number of parts flowing between each two
facilities in the construction site. This variable is assumed to have five
membership functions as shown in Fig. 6.
2) Information flow (IF): defined by the number of communications (oral or
reports) between facilities. It is also assumed that this variable has five
membership functions as shown in Fig. 7.
3) Equipment flow (EF): defined by the number of material handling equipment
(trucks, mixers, etc.) used to transfer materials between facilities. This variable
is also assumed to have five membership functions as shown in Fig. 8.

![Fig. 6: Membership functions of material flow (MF).](image-url)
Based on the input variables mentioned earlier, the planner assigns a closeness rating (R) to each decision rule as an output variable. As shown in Fig. 9, the closeness rating (R) is assumed to take six membership functions (X for undesirable, U for unimportant, O for ordinary, I for important, E for especially important, and A for absolutely important).

Fig. 9: Membership functions of closeness rating (R).
Generating the Weight Factors

Assuming the planner was able to collect the information tabulated in Table 1 for the relationships of all factors in the layout, the weight of each factor is calculated as suggested by Saaty (1980). The numbers shown for the intensity importance of factors (\(a_{ij}\)) range from 1 for equal importance of factor i over factor j to 9 for absolute importance of factor i over factor j, where \(a_{ij}=1/a_{ji}\) (Saaty 1980). These numbers represent the true preference of each factor with respect to other factors. If the relationship between facilities 1 (offices) and 2 (warehouse) is under consideration, for example, the planner is assigning a value of 2 for the importance of factor 2 over factor 3. This means that there is a range between an equal and a weak importance of factor 2 over factor 3. On the other hand, the value of 9 assigned for the importance of factor 2 over factor 3 (considering the relationship between facilities 1 and 6) indicates an absolute importance of factor 2 over factor 3. The information shown in Table 1, however, were based on the personal judgment of the authors’ previous experience in construction projects. Considering the relationship between facility 1 (offices) and facility 3 (batch plant), for example, the intensity importance of factors listed in Table 1 are used to calculate the weights of factors (\(P_i\)) shown in Table 2 below. These weights of factors are calculated in the following steps, as described in Saaty (1980):

Table 1. Relationships and intensity importance of factors among all facilities.

<table>
<thead>
<tr>
<th>Facilities</th>
<th>Factor 1</th>
<th>Factor 2</th>
<th>Factor 3</th>
<th>Intensity Importance of Factors</th>
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<td></td>
<td>MF</td>
<td>IF</td>
<td>EF</td>
<td>1 over 2</td>
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<td>1-2</td>
<td>0</td>
<td>12</td>
<td>0</td>
<td>0.5</td>
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<td>1-3</td>
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<td>2-3</td>
<td>1200</td>
<td>13</td>
<td>10</td>
<td>1.5</td>
</tr>
<tr>
<td>2-4</td>
<td>150</td>
<td>3</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>2-5</td>
<td>100</td>
<td>5</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>2-6</td>
<td>1500</td>
<td>7</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>3-4</td>
<td>0</td>
<td>3</td>
<td>3</td>
<td>0.8</td>
</tr>
<tr>
<td>3-5</td>
<td>400</td>
<td>26</td>
<td>2</td>
<td>0.8</td>
</tr>
<tr>
<td>3-6</td>
<td>1000</td>
<td>5</td>
<td>5</td>
<td>4</td>
</tr>
<tr>
<td>4-5</td>
<td>0</td>
<td>2</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>4-6</td>
<td>0</td>
<td>0</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>5-6</td>
<td>5</td>
<td>0</td>
<td>1</td>
<td>1.25</td>
</tr>
</tbody>
</table>
1) Multiplying the $n$ elements in each row of the shaded matrix shown in Table 2 to get the result $X_i$, where $n$ is the number of factors and equals to 3 in this study.

2) Take the $n$th root of $(X_i)$ for each row. The result is $(Y_i)$.

3) Normalize by dividing each number $(Y_i)$ by the sum of all the numbers $(\sum Y_i)$. The result is the weight factors $P_i$.

Table 2. The weight factors between facilities 1 & 3 ($a_{ij}$).

<table>
<thead>
<tr>
<th>$i/j$</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>$X_i (=1 \times 2 \times 3)$</th>
<th>$Y_i (=X^{.333})$</th>
<th>$P_i = (WF) = Y_i / \sum Y_i$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>0.5</td>
<td>1</td>
<td>0.5</td>
<td>0.794</td>
<td>0.240</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>1</td>
<td>3</td>
<td>6</td>
<td>1.817</td>
<td>0.550</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>0.333</td>
<td>1</td>
<td>0.333</td>
<td>0.693</td>
<td>0.210</td>
</tr>
</tbody>
</table>

This process is repeated for all pairs of facilities and results are listed in appendix A. The weight factor is considered one of the input factors that will influence the layout. The higher the weight factor, the more important the factor when planning the layout. The weight factor is fuzzified as shown in Fig. 10.

![Fig. 10: Membership functions of weight factor (WF).](image)

Establishing the IF-THEN Decision Rules

At this point, the fuzzification process is complete. The next step is to establish the decision-making logic (decision rules). These rules usually take the form of the IF-THEN rules. The number of decision rules between each factor and its weight factor is calculated using the equation: $R = (m)^v = (5)^2 = 25$, where $R$= number of rules, $m$= number of membership functions, and $v$= number of input variables. Since we are considering three input variables that will affect the decision of the planner, the total number of rules between each two facilities is equal to $3 \times 25 = 75$ rules. These rules were compiled based on the personal judgment of the authors' previous
experience in construction projects. The rules are shown in Fig. 11 and listed in appendix B.

<table>
<thead>
<tr>
<th>MF/WF</th>
<th>VL</th>
<th>L</th>
<th>M</th>
<th>H</th>
<th>VH</th>
</tr>
</thead>
<tbody>
<tr>
<td>VL</td>
<td>U</td>
<td>U</td>
<td>O</td>
<td>O</td>
<td>I</td>
</tr>
<tr>
<td>L</td>
<td>U</td>
<td>O</td>
<td>O</td>
<td>I</td>
<td>E</td>
</tr>
<tr>
<td>M</td>
<td>O</td>
<td>O</td>
<td>I</td>
<td>E</td>
<td>E</td>
</tr>
<tr>
<td>H</td>
<td>O</td>
<td>I</td>
<td>E</td>
<td>E</td>
<td>A</td>
</tr>
<tr>
<td>VH</td>
<td>I</td>
<td>E</td>
<td>E</td>
<td>A</td>
<td>A</td>
</tr>
</tbody>
</table>

(a)

<table>
<thead>
<tr>
<th>IF/WF</th>
<th>VL</th>
<th>L</th>
<th>M</th>
<th>H</th>
<th>VH</th>
</tr>
</thead>
<tbody>
<tr>
<td>VL</td>
<td>U</td>
<td>U</td>
<td>U</td>
<td>O</td>
<td>O</td>
</tr>
<tr>
<td>L</td>
<td>U</td>
<td>O</td>
<td>O</td>
<td>I</td>
<td>E</td>
</tr>
<tr>
<td>M</td>
<td>U</td>
<td>O</td>
<td>O</td>
<td>I</td>
<td>E</td>
</tr>
<tr>
<td>H</td>
<td>O</td>
<td>O</td>
<td>I</td>
<td>E</td>
<td>A</td>
</tr>
<tr>
<td>VH</td>
<td>O</td>
<td>I</td>
<td>E</td>
<td>A</td>
<td>A</td>
</tr>
</tbody>
</table>

(b)

<table>
<thead>
<tr>
<th>EF/WF</th>
<th>VL</th>
<th>L</th>
<th>M</th>
<th>H</th>
<th>VH</th>
</tr>
</thead>
<tbody>
<tr>
<td>VL</td>
<td>U</td>
<td>U</td>
<td>O</td>
<td>I</td>
<td>I</td>
</tr>
<tr>
<td>L</td>
<td>U</td>
<td>O</td>
<td>I</td>
<td>I</td>
<td>E</td>
</tr>
<tr>
<td>M</td>
<td>O</td>
<td>I</td>
<td>I</td>
<td>E</td>
<td>E</td>
</tr>
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<td>H</td>
<td>I</td>
<td>I</td>
<td>E</td>
<td>E</td>
<td>A</td>
</tr>
<tr>
<td>VH</td>
<td>I</td>
<td>E</td>
<td>E</td>
<td>A</td>
<td>A</td>
</tr>
</tbody>
</table>

(c)

U= unimportant, O= ordinary, I= important, E= especially important, A= absolutely important, VL= very low, L= low, M= medium, H= high, and VH= very high.

Fig. 11: IF-THEN rules of (a) material flow (MF) and its weight factor (WF); (b) information flow (IF) and its weight factor; and equipment flow (EF) and its weight factor.

Developing a Program for the Inference of the Decision Rules to Generate the Facility Relationship Chart (FRC)

A program using Visual Basic programming language was developed to deal with the inference of the generated IF-THEN decision rules. The program can use both the max-min and max-product composition rules of inference. It also allows the user to chose any of the defuzzification methods such as the centroid of the area (COA), mean of maximum (MOM), smallest of maximum (SOM), or the largest of maximum (LOM). In this study, the max-min composition rule of inference and the centroid of the area (COA) were used for the defuzzification process required to generate the final output crisp values of the facility relationship chart. These values can then be used in the next step to develop the most efficient layout. This fuzzy decision-making process is repeated for each pair of facilities (i.e., 15 times). Parts of the program showing the use of the max-min composition rule of inference and the centroid of the area (COA) method are illustrated in Fig. 12 and Fig. 13, respectively. The complete program is listed in appendix C.
If DialogSheets("Dialog3").OptionButtons("MaxMin Option").Value = xlOn Then infrule = "MaxMin"
Else
    infrule = ActiveCell.Value
End If
Worksheets("data1").Activate: Range("Mf1").Select: ActiveCell.Offset(0, 11).Select
For j = 1 To nrul
    If yfire(j) = 0 Then GoTo newrule
    If infrule = "MaxMin" Then
        If mftype(l, r(j)) = "trian" Then
            x1fir(j) = (x2(l, r(j)) - x1(l, r(j))) * yfire(j) / y2(l, r(j)) + x1(l, r(j))
            x2fir(j) = x3(l, r(j)) - (x3(l, r(j)) - x2(l, r(j))) * yfire(j) / y2(l, r(j))
        Else
            x1fir(j) = (x2(l, r(j)) - x1(l, r(j))) * yfire(j) / y2(l, r(j)) + x1(l, r(j))
            x2fir(j) = x4(l, r(j)) - (x4(l, r(j)) - x3(l, r(j))) * yfire(j) / y3(l, r(j))
        End If
    Else
        If mftype(l, r(j)) = "trian" Then
            x1fir(j) = x2(l, r(j)): x2fir(j) = x2(l, r(j))
        Else
            x1fir(j) = x2(l, r(j)): x2fir(j) = x3(l, r(j))
        End If
    End If
End If
newrule:
ActiveCell.Value = x1fir(j): ActiveCell.Offset(0, 1).Select: ActiveCell.Value = x2fir(j)
ActiveCell.Offset(1, -1).Select
Next j

Fig. 12: The part of the visual basic program used to perform the max-min rule of inference.

If DialogSheets("Dialog3").OptionButtons("COA Option").Value = xlOn Then
    TArea = 0: Tmoa = 0
    For i = 1 To s1 - 1
        area(i) = xinter * ((yover(i + 1) + yover(i)) / 2)
        moa(i) = area(i) * (xinter / 2 + xover(i))
        TArea = TArea + area(i)
        Tmoa = Tmoa + moa(i)
    Next i
    Fout = Tmoa / TArea
End If

Fig. 13: The part of the visual basic program used to perform the COA defuzzification method.

When running the program, the following information are required to be entered to the program as inputs:
1) Number of variables, as shown in the screen capture of Fig. 13 (a) below. The
figure shows the number of variables (each variable, its weight factor, and the closeness rating).

2) Number of membership functions for each variable and the values for each membership function. For example, Fig. 13 (b) below shows the number of membership functions for the first variable, which is the material flow, while Fig. 14 shows the x-values of the second membership function (low) of this variable.

![Fig. 13: (a) Number of input variables; (b) number of membership functions for the material flow.](image1)

![Fig. 14: Values of the second membership function (low) for the material flow.](image2)
3) The input value of the first variable (for example, 150 for material flow between facilities 2 and 4, as given in table 1) and the input value of the second variable (for example, 0.333 for weight factor of material flow between facilities 2 and 4). The two values are shown in Fig. 15 and Fig. 16, respectively.

**Fig. 15: The input value of the first variable (MF) between facilities 2 and 4.**

![Fuzzy Inference Program](image1)

**Fig. 16: The input value of the second variable (WF) of (MF) between facilities 2 and 4.**

![Fuzzy Inference Program](image2)

4) The total number of rules between each variable and its weight factor. For example, 25 rules between material flow and its weight factor, as shown in Fig. 17 below.

**Fig. 17: The total number of rules between (MF) and its (WF).**

![Fuzzy Inference Program](image3)
5) The membership function of each variable in each rule. For example, rule number 1 shown in Fig. 18 below represents the rule: IF MF is (VL) and WF is (VL) THEN R is U.

![Fig. 18: The membership functions of each variable in rule number 1.](image)

6) The fuzzy inference and defuzzification methods (Fig. 19).

![Fig. 19: The fuzzy inference and defuzzification methods](image)
The input values for each variable shown in Table 1 were then entered to the program for each pair of facilities along with its corresponding weight factor to get the overall membership functions and their output crisp values. For example, Fig. 20 illustrates the overall membership functions of facilities 2 and 4. The max-min firing rules for this pair of facilities are shown in appendix D while the overall membership functions of each pair of facilities are listed in appendix E.

The average of output crisp values (closeness ratings) for each pair of facilities is calculated in Table 3 below. These ratings are tabulated in the facility relationship chart (Fig. 21), which will be used in the next step to generate the facilities’ layout in the construction site.

**Table 3. The average closeness rating values.**

<table>
<thead>
<tr>
<th>Activity</th>
<th>MF/WF</th>
<th>IF/WF</th>
<th>EF/WF</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-2</td>
<td>2.638</td>
<td>4.163</td>
<td>2.638</td>
<td>3.146</td>
</tr>
<tr>
<td>1-3</td>
<td>2.582</td>
<td>4.592</td>
<td>2.421</td>
<td>3.198</td>
</tr>
<tr>
<td>1-4</td>
<td>3.001</td>
<td>2.759</td>
<td>3.501</td>
<td>3.087</td>
</tr>
<tr>
<td>1-5</td>
<td>2.150</td>
<td>6.001</td>
<td>2.150</td>
<td>3.434</td>
</tr>
<tr>
<td>1-6</td>
<td>2.35</td>
<td>6</td>
<td>2.35</td>
<td>3.567</td>
</tr>
<tr>
<td>2-3</td>
<td>5.523</td>
<td>3.001</td>
<td>5.303</td>
<td>4.609</td>
</tr>
<tr>
<td>2-4</td>
<td>3.265</td>
<td>2.582</td>
<td>4.001</td>
<td>3.283</td>
</tr>
<tr>
<td>2-5</td>
<td>4.036</td>
<td>2.972</td>
<td>2.628</td>
<td>3.212</td>
</tr>
<tr>
<td>2-6</td>
<td>6</td>
<td>2.25</td>
<td>5</td>
<td>4.583</td>
</tr>
<tr>
<td>3-4</td>
<td>2.110</td>
<td>2.405</td>
<td>5.001</td>
<td>3.172</td>
</tr>
<tr>
<td>3-5</td>
<td>4.100</td>
<td>5.667</td>
<td>2.928</td>
<td>4.231</td>
</tr>
<tr>
<td>3-6</td>
<td>6.5</td>
<td>2.25</td>
<td>5</td>
<td>4.583</td>
</tr>
<tr>
<td>4-5</td>
<td>3.001</td>
<td>2.421</td>
<td>3.501</td>
<td>2.975</td>
</tr>
<tr>
<td>4-6</td>
<td>3.200</td>
<td>2.200</td>
<td>4.200</td>
<td>3.200</td>
</tr>
<tr>
<td>5-6</td>
<td>3.35</td>
<td>2.05</td>
<td>4.5</td>
<td>3.300</td>
</tr>
</tbody>
</table>
Developing the Physical Layout of Facilities

After the facility relationship chart is generated as explained in the previous step, a genetic algorithms program was used to generate the layout. The program was developed by Mr. Emad El-Beltagi, a PhD student who is currently working on the program as a part of his research work.

The program requires the user to enter the number of facilities to be located in the site, the area of each facility, and the area of the construction site (Fig. 22). The figure shows that construction site is divided into 418 square units (selected as 19X22 units). Each unit has an area of 20 m².

Construction site area = 98.387mx84.971m= 8360 m².

Fig. 21: Facility relationship chart.

Fig. 22: The user interface of the genetic algorithm program.
As shown in Table 4 below, the user is required to enter to the program the start unit number for fixed facilities in the site (such as roads, building to be constructed, etc.). The program also requires that fixed facilities should be given the number (1), while other facilities to be given the number (0). Table 4 also summarizes the required inputs for each facility in the construction site. Due to the L shape of the building to be constructed in the site, it is divided into two parts (building 1 and building 2). This is to enable the program to place the building in its required location.

Table 4. Required inputs for each facility.

<table>
<thead>
<tr>
<th>Facility No.</th>
<th>Facility Name</th>
<th>Area(m2)</th>
<th>No. of Units</th>
<th>Facility Status 1=fixed, 0=free for fixed facilities</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Offices</td>
<td>160</td>
<td>8</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>Warehouse</td>
<td>240</td>
<td>12</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>Batch plant</td>
<td>500</td>
<td>25</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>Workshop</td>
<td>120</td>
<td>6</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>Quality control</td>
<td>60</td>
<td>3</td>
<td>0</td>
</tr>
<tr>
<td>6</td>
<td>Building 1</td>
<td>1440</td>
<td>72</td>
<td>1 113</td>
</tr>
<tr>
<td></td>
<td>Building 2</td>
<td>1440</td>
<td>72</td>
<td>1 251</td>
</tr>
</tbody>
</table>

Building 1: 1440 m²
Building 2: 1440 m²

The site area = 8360 m².

To evaluate the goodness of a possible layout, an objective function was constructed by multiplying the desired closeness rating values between each two facilities by the actual distance between them, and summing up for all facilities. The objective function, as such, represents the total travel distance associated with a given site layout. Accordingly, Minimizing this objective function is required in order to arrive at the optimum layout that brings the least travel distance. Evaluating the total travel distance of a given site layout involves determining the distances between them. Considering the simplified site layout of Fig. 23, the distance \( d_{ab} \) between facilities "a" and "b" is:

\[
\text{distance } d_{ab} = \sqrt{(X_a - X_b)^2 + (Y_a - Y_b)^2} = \sqrt{(3-9)^2 + (6.5-10)^2} = 6.95
\]

Using the distance calculations, The total travel distance (objective function) of a site layout with \( n \) facilities can be calculated as follows:

\[
\text{Total travel distance (objective function)} = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} d_{ij} R_{ij}
\]

Where, \( R_{ij} \) is the desired closeness rating value between facilities \( i \) and \( j \).
Fig. 23: Distance between facilities.

In the program, the user is given the flexibility to input the population size and the number of offspring generations, as shown in the screen captures of Figs. 24 and 25, respectively.

Notes:
Origin O (0, 0)
Point A (3, 6.5)
Point B (9, 10)

Fig. 24: The selected population size.
After entering the facilities data to the program, the values for the closeness rating between each pair of facilities were taken from the results of the fuzzy inference program (Fig. 21) and was input to the program. The next step is to enter the required population size (Fig. 24) and the required number of generations per cycle (Fig. 25), which were selected as 100 and 50, respectively. After all the required inputs were entered as explained above, the genetic algorithms program generated different solutions (layouts) with their corresponding fitness values (scores), listed in appendix F. The best solution, basically, is the one with the minimum score (minimum fitness value).

Evaluating the Generated Layouts

The final step is to evaluate the best layouts, which is normally performed by the designer. Depending on the judgement of the designer, one layout should finally be selected which may not be the one with the best (minimum) score. Based on the personal experience of the authors, solution number 6 (shown in appendix F) was selected for the layout of the example presented in this study. This solution has a score of 622 as opposed to the solution with the minimum score (595). The selected layout is shown in Fig. 26. The shaded area in the figure represents the L-shaped building to be constructed (facility number 6). It is noticed that the offices (facility number 1) were placed near the building, which is a logical arrangement as compared to real life situations. On the other hand, the workshop (facility number 4) was placed far from the building which is also considered to be a logical placement. This is because there is no strong relation between the workshop and the building to be constructed. Also, the batch plant and the storage (facilities 2 and 3) were placed adjacent to each other. This is because of the strong relationship (closeness rating of 4.609) assigned to these two facilities.
COMMENTS AND DISCUSSION

One of the drawbacks of the proposed approach is the difficulties associated with generating the membership functions of the variables affecting the decision of the planner. Another disadvantage is the problem of establishing the decision rules, which requires a great deal of care and experience. In some situations also, the planner may not efficiently decide the values for the intensity importance of factors. This is particularly true when the number of facilities increases resulting, therefore, in complex relationships between the different facilities. Often, however, site planners have adequate experience to overcome such problems.

On the other hand, the main characteristics of the proposed approach that makes it an efficient system for site layout planning include:

- It allows the designer (site planner) to use all possible factors affecting the layout and utilize these factors in a scientific way instead of relying on pure
- It provides different alternative solutions to the site layout and considers the total travel distance as an objective function;
- It has been implemented on a commercial spreadsheet program that is customary to many practitioners in construction; and
- This fuzzy decision-making approach can be adapted to many applications other than the facility layout planning.

**CONCLUSION**

In this project, a methodology was proposed based on the fuzzy set theory to generate the closeness rating values, which represent the relationships between each pair of facilities in a construction site. This was achieved using a visual basic spreadsheet program to utilize its familiar interface and powerful functions. The program performs the fuzzification of the input variables, the fuzzy inference, and the defuzzification process. The final crisp values (closeness ratings) obtained by the defuzzification process were entered into a genetic algorithms program to optimally place facilities within a construction site. An example application was presented to demonstrate the practicality and powerful capabilities of the approach and the results were then discussed. The results of the layout indicated an agreement with the real-life logical arrangement of temporary facilities in construction sites. Finally, the advantages and limitations of the proposed approach were outlined.
REFERENCES


APPENDICES

Appendix A: The Weight Factors Between Each Pair of Facilities.

1) Facilities 1 & 2:

<table>
<thead>
<tr>
<th>i/j</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>X_i (=1X2X3)</th>
<th>Y_i (=X^0.333)</th>
<th>P_i (=WF) = Y_i/ΣY_i</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>0.5</td>
<td>1</td>
<td>0.5</td>
<td>0.794</td>
<td>0.250</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>4</td>
<td>1.587</td>
<td>0.500</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>0.5</td>
<td>1</td>
<td>0.5</td>
<td>0.794</td>
<td>0.250</td>
</tr>
<tr>
<td>ΣY_i</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3.175</td>
<td></td>
</tr>
</tbody>
</table>

2) Facilities 1 & 3:

<table>
<thead>
<tr>
<th>i/j</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>X_i (=1X2X3)</th>
<th>Y_i (=X^0.333)</th>
<th>P_i (=WF) = Y_i/ΣY_i</th>
</tr>
</thead>
<tbody>
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7) Facilities 2 & 4:

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8) Facilities 2 & 5:

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10) Facilities 3 & 4:

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<th>( P_i = (WF) = Y_i / \sum Y_i )</th>
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<tbody>
<tr>
<td>1</td>
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\( \sum Y_i = 3.572 \)

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<th>( P_i = (WF) = Y_i / \sum Y_i )</th>
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\( \sum Y_i = 3.000 \)

14) Facilities 4 & 6:

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\( \sum Y_i = 3.016 \)

15) Facilities 5 & 6:

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\( \sum Y_i = 3.016 \)
Appendix B: Decision Rules.

1) Inference rules between material flow and its weight factor:

Rule 1: IF (MF) is VL AND its (WF) is VL THEN Rating (R) is U
Rule 2: IF (MF) is VL AND its (WF) is L THEN Rating (R) is U
Rule 3: IF (MF) is VL AND its (WF) is M THEN Rating (R) is O
Rule 4: IF (MF) is VL AND its (WF) is H THEN Rating (R) is O
Rule 5: IF (MF) is VL AND its (WF) is VH THEN Rating (R) is I
Rule 6: IF (MF) is L AND its (WF) is VL THEN Rating (R) is U
Rule 7: IF (MF) is L AND its (WF) is L THEN Rating (R) is O
Rule 8: IF (MF) is L AND its (WF) is M THEN Rating (R) is O
Rule 9: IF (MF) is L AND its (WF) is H THEN Rating (R) is I
Rule 10: IF (MF) is L AND its (WF) is VH THEN Rating (R) is I
Rule 11: IF (MF) is M AND its (WF) is VL THEN Rating (R) is O
Rule 12: IF (MF) is M AND its (WF) is L THEN Rating (R) is O
Rule 13: IF (MF) is M AND its (WF) is M THEN Rating (R) is I
Rule 14: IF (MF) is M AND its (WF) is H THEN Rating (R) is E
Rule 15: IF (MF) is M AND its (WF) is VH THEN Rating (R) is E
Rule 16: IF (MF) is H AND its (WF) is VL THEN Rating (R) is O
Rule 17: IF (MF) is H AND its (WF) is L THEN Rating (R) is I
Rule 18: IF (MF) is H AND its (WF) is M THEN Rating (R) is E
Rule 19: IF (MF) is H AND its (WF) is H THEN Rating (R) is E
Rule 20: IF (MF) is H AND its (WF) is VH THEN Rating (R) is A
Rule 21: IF (MF) is VH AND its (WF) is VL THEN Rating (R) is I
Rule 22: IF (MF) is VH AND its (WF) is L THEN Rating (R) is E
Rule 23: IF (MF) is VH AND its (WF) is M THEN Rating (R) is E
Rule 24: IF (MF) is VH AND its (WF) is H THEN Rating (R) is A
Rule 25: IF (MF) is VH AND its (WF) is VH THEN Rating (R) is A

2) Inference rules between information flow and its weight factor:

Rule 1: IF (IF) is VL AND its (WF) is VL THEN Rating (R) is U
Rule 2: IF (IF) is VL AND its (WF) is L THEN Rating (R) is U
Rule 3: IF (IF) is VL AND its (WF) is M THEN Rating (R) is U
Rule 4: IF (IF) is VL AND its (WF) is H THEN Rating (R) is O
Rule 5: IF (IF) is VL AND its (WF) is VH THEN Rating (R) is O
Rule 6: IF (IF) is L AND its (WF) is VL THEN Rating (R) is U
Rule 7: IF (IF) is L AND its (WF) is L THEN Rating (R) is U
Rule 8: IF (IF) is L AND its (WF) is M THEN Rating (R) is O
Rule 9: IF (IF) is L AND its (WF) is H THEN Rating (R) is O
Rule 10: IF (IF) is L AND its (WF) is VH THEN Rating (R) is I

Rule 11: IF (IF) is M AND its (WF) is VL THEN Rating (R) is U
Rule 12: IF (IF) is M AND its (WF) is L THEN Rating (R) is O
Rule 13: IF (IF) is M AND its (WF) is M THEN Rating (R) is O
Rule 14: IF (IF) is M AND its (WF) is H THEN Rating (R) is I
Rule 15: IF (IF) is M AND its (WF) is VH THEN Rating (R) is E

Rule 16: IF (IF) is H AND its (WF) is VL THEN Rating (R) is O
Rule 17: IF (IF) is H AND its (WF) is L THEN Rating (R) is O
Rule 18: IF (IF) is H AND its (WF) is M THEN Rating (R) is I
Rule 19: IF (IF) is H AND its (WF) is H THEN Rating (R) is E
Rule 20: IF (IF) is H AND its (WF) is VH THEN Rating (R) is A

Rule 21: IF (IF) is VH AND its (WF) is VL THEN Rating (R) is O
Rule 22: IF (IF) is VH AND its (WF) is L THEN Rating (R) is I
Rule 23: IF (IF) is VH AND its (WF) is M THEN Rating (R) is E
Rule 24: IF (IF) is VH AND its (WF) is H THEN Rating (R) is A
Rule 25: IF (IF) is VH AND its (WF) is VH THEN Rating (R) is A

3) Inference rules between equipment flow and its weight factor:

Rule 1: IF (EF) is VL AND its (WF) is VL THEN Rating (R) is U
Rule 2: IF (EF) is VL AND its (WF) is L THEN Rating (R) is U
Rule 3: IF (EF) is VL AND its (WF) is M THEN Rating (R) is O
Rule 4: IF (EF) is VL AND its (WF) is H THEN Rating (R) is I
Rule 5: IF (EF) is VL AND its (WF) is VH THEN Rating (R) is I

Rule 6: IF (EF) is L AND its (WF) is VL THEN Rating (R) is U
Rule 7: IF (EF) is L AND its (WF) is L THEN Rating (R) is O
Rule 8: IF (EF) is L AND its (WF) is M THEN Rating (R) is I
Rule 9: IF (EF) is L AND its (WF) is H THEN Rating (R) is I
Rule 10: IF (EF) is L AND its (WF) is VH THEN Rating (R) is E
Rule 11: IF (EF) is M AND its (WF) is VL THEN Rating (R) is O
Rule 12: IF (EF) is M AND its (WF) is L THEN Rating (R) is I
Rule 13: IF (EF) is M AND its (WF) is M THEN Rating (R) is I
Rule 14: IF (EF) is M AND its (WF) is H THEN Rating (R) is E
Rule 15: IF (EF) is M AND its (WF) is VH THEN Rating (R) is E

Rule 16: IF (EF) is H AND its (WF) is VL THEN Rating (R) is I
Rule 17: IF (EF) is H AND its (WF) is L THEN Rating (R) is I
Rule 18: IF (EF) is H AND its (WF) is M THEN Rating (R) is E
Rule 19: IF (EF) is H AND its (WF) is H THEN Rating (R) is E
Rule 20: IF (EF) is H AND its (WF) is VH THEN Rating (R) is E

Rule 21: IF (EF) is VH AND its (WF) is VL THEN Rating (R) is I
Rule 22: IF (EF) is VH AND its (WF) is L THEN Rating (R) is E
Rule 23: IF (EF) is VH AND its (WF) is M THEN Rating (R) is E
Rule 24: IF (EF) is VH AND its (WF) is H THEN Rating (R) is A
Rule 25: IF (EF) is VH AND its (WF) is VH THEN Rating (R) is A
Appendix C: Visual Basic Program Listing.

Public inp, i, j, k As Integer
Public nomf() As Integer
Public tout As Double
Public nrul As Integer
Public nr As Integer
Public xinter As Single
Public TArea As Single
Public mftype() As String
Public connect() As String
Public x1(), x2(), x3(), x4(), y1(), y2(), y3(), y4() As Single
Public x() As Single
Public y() As Single
Public yfire() As Single
Public yover() As Single
Public xover() As Single
Public v1(), v2(), v3(), v4(), v5(), v6(), v7() As Integer
Public m1(), m2(), m3(), m4(), m5(), m6(), m7() As Integer
Public z1(), z2(), z3(), z4(), z5(), z6(), z7() As Single
Public x1fir(), x2fir() As Single
Public Zmin(), Zmax() As Single
Public slope() As Single
Public Xmin(), Xmax() As Single

Sub Data1()
Application.ScreenUpdating = False

methodofinp = Val(InputBox("Inter 1 for using interface windows, or 2 for using spreadsheet", "Fuzzy Inference Program", "1"))
If methodofinp = 1 Then
    inp = Val(InputBox("How many input variables?", "Fuzzy Inference Program", "2"))
Else
    Worksheets("data").Select: Range("NVariables").Select: inp = ActiveCell.Value
End If
ReDim nomf(inp) As Integer
ReDim Xmin(inp), Xmax(inp) As Single
k = 0
Worksheets("data").Select: Range("NMF").Select
For i = 1 To inp
    If methodofinp = 1 Then
        nomf(i) = Val(InputBox("How many membership functions per variable " & i & ",", "Fuzzy Inference Program", "1"))
    Else
        nomf(i) = ActiveCell.Value: ActiveCell.Offset(0, 1).Select
    End If
    If nomf(i) > k Then k = nomf(i)
Next i
ReDim mftype(inp, k) As String
ReDim x1(inp, k), x2(inp, k), x3(inp, k), x4(inp, k), y1(inp, k), y2(inp, k), y3(inp, k), y4(inp, k) As Single
Worksheets("data").Select: Range("MFType").Select
For i = 1 To inp
    Xmax(i) = -10000: Xmin(i) = 10000
    For j = 1 To nomf(i)
        If methodofinp = 1 Then
            DialogSheets("Dialog1").Labels("Var No label").Caption = "Variable " & i
            DialogSheets("Dialog1").Labels("Mf No label").Caption = "Membership function " & j
            DialogSheets("Dialog1").Show
            If DialogSheets("Dialog1").OptionButtons("Trian Option").Value = xlOn Then
                mftype(i, j) = "trian"
                With DialogSheets("Dialog1")
                    x1(i, j) = Val(EditBoxes("First Val Edit").Caption)
                    If x1(i, j) > Xmax(i) Then Xmax(i) = x1(i, j)
                    If x1(i, j) < Xmin(i) Then Xmin(i) = x1(i, j)
                    y1(i, j) = 0
                    x2(i, j) = Val(EditBoxes("Second Val Edit").Caption)
                    If x2(i, j) > Xmax(i) Then Xmax(i) = x2(i, j)
                    If x2(i, j) < Xmin(i) Then Xmin(i) = x2(i, j)
                    y2(i, j) = 1
                    x3(i, j) = Val(EditBoxes("Third Val Edit").Caption)
                    If x3(i, j) > Xmax(i) Then Xmax(i) = x3(i, j)
                    If x3(i, j) < Xmin(i) Then Xmin(i) = x3(i, j)
                    y3(i, j) = 0
                End With
            Else
                mftype(i, j) = "trap"
                With DialogSheets("Dialog1")
                    x1(i, j) = Val(EditBoxes("First Val Edit").Caption)
                    If x1(i, j) > Xmax(i) Then Xmax(i) = x1(i, j)
                    If x1(i, j) < Xmin(i) Then Xmin(i) = x1(i, j)
                    y1(i, j) = 0
                    x2(i, j) = Val(EditBoxes("Second Val Edit").Caption)
                    If x2(i, j) > Xmax(i) Then Xmax(i) = x2(i, j)
                    If x2(i, j) < Xmin(i) Then Xmin(i) = x2(i, j)
                    y2(i, j) = 1
                    x3(i, j) = Val(EditBoxes("Third Val Edit").Caption)
                    If x3(i, j) > Xmax(i) Then Xmax(i) = x3(i, j)
                    If x3(i, j) < Xmin(i) Then Xmin(i) = x3(i, j)
                    y3(i, j) = 1
                    x4(i, j) = Val(EditBoxes("Fourth Val Edit").Caption)
                    If x4(i, j) > Xmax(i) Then Xmax(i) = x4(i, j)
                    If x4(i, j) < Xmin(i) Then Xmin(i) = x4(i, j)
                    y4(i, j) = 0
                End With
            End If
        Else
            mftype(i, j) = ActiveCell.Value
            If mftype(i, j) = "trian" Then
                ActiveCell.Offset(0, 1).Select: x1(i, j) = ActiveCell.Value
                If x1(i, j) > Xmax(i) Then Xmax(i) = x1(i, j)
                If x1(i, j) < Xmin(i) Then Xmin(i) = x1(i, j)
                y1(i, j) = 0: ActiveCell.Offset(0, 1).Select: x2(i, j) = ActiveCell.Value
                If x2(i, j) > Xmax(i) Then Xmax(i) = x2(i, j)
                If x2(i, j) < Xmin(i) Then Xmin(i) = x2(i, j)
                y2(i, j) = 1: ActiveCell.Offset(0, 1).Select: x3(i, j) = ActiveCell.Value
                If x3(i, j) > Xmax(i) Then Xmax(i) = x3(i, j)
                If x3(i, j) < Xmin(i) Then Xmin(i) = x3(i, j)
                y3(i, j) = 0
            Else
                mftype(i, j) = ActiveCell.Value
            End If
        End If
    End For
End For
y3(i, j) = 0: ActiveCell.Offset(1, -3).Select
Else
    ActiveCell.Offset(0, 1).Select: x1(i, j) = ActiveCell.Value
    If x1(i, j) > Xmax(i) Then Xmax(i) = x1(i, j): If x1(i, j) < Xmin(i) Then Xmin(i) = x1(i, j)
y1(i, j) = 0: ActiveCell.Offset(0, 1).Select: x2(i, j) = ActiveCell.Value
    If x2(i, j) > Xmax(i) Then Xmax(i) = x2(i, j): If x2(i, j) < Xmin(i) Then Xmin(i) = x2(i, j)
y2(i, j) = 1: ActiveCell.Offset(0, 1).Select: x3(i, j) = ActiveCell.Value
    If x3(i, j) > Xmax(i) Then Xmax(i) = x3(i, j): If x3(i, j) < Xmin(i) Then Xmin(i) = x3(i, j)
y3(i, j) = 1: ActiveCell.Offset(0, 1).Select: x4(i, j) = ActiveCell.Value
    If x4(i, j) > Xmax(i) Then Xmax(i) = x4(i, j): If x4(i, j) < Xmin(i) Then Xmin(i) = x4(i, j)
y4(i, j) = 0: ActiveCell.Offset(1, -4).Select
End If
End If
Next j
Next i
Worksheets("data1").Select
Range("Fdata").ClearContents: Range("start").Select
Range("Start").Value = "No of Variables": ActiveCell.Offset(0, 1).Select: ActiveCell.Value = inp
Range("variable").Select
ActiveCell.Value = "Variable No": ActiveCell.Offset(0, 1).Select: ActiveCell.Value = "No. of MF"
ActiveCell.Offset(0, 1).Select: ActiveCell.Value = "Xmin": ActiveCell.Offset(0, 1).Select:
ActiveCell.Value = "Xmax"
For i = 1 To inp
    Range("variable").Select: ActiveCell.Offset(i, 0).Select
    ActiveCell.Value = i: ActiveCell.Offset(0, 1).Select: ActiveCell.Value = nomf(i)
    ActiveCell.Offset(0, 1).Select: ActiveCell.Value = Xmin(i): ActiveCell.Offset(0, 1).Select:
    ActiveCell.Value = Xmax(i)
Next i

Range("MF").Select: ActiveCell.Value = "Variable No": ActiveCell.Offset(0, 1).Select: ActiveCell.Value = "MF No"
ActiveCell.Offset(0, 1).Select: ActiveCell.Value = "MF Type": ActiveCell.Offset(0, 1).Select:
ActiveCell.Value = "Pint 1"
ActiveCell.Offset(0, 1).Select: ActiveCell.Value = "Point 2": ActiveCell.Offset(0, 1).Select:
ActiveCell.Value = "Point 3"
ActiveCell.Offset(0, 1).Select: ActiveCell.Value = "Point 4": ActiveCell.Offset(0, 1).Select:
ActiveCell.Value = "X"
ActiveCell.Offset(0, 1).Select: ActiveCell.Value = "Y": ActiveCell.Offset(0, 1).Select: ActiveCell.Value = "Rule no"
ActiveCell.Offset(0, 1).Select: ActiveCell.Value = "Yfir": ActiveCell.Offset(0, 1).Select:
ActiveCell.Value = "X1fir"
ActiveCell.Offset(0, 1).Select: ActiveCell.Value = "X2fir"
Range("MF1").Select
For i = 0 To inp - 1
    ActiveCell.Value = i + 1: ActiveCell.Offset(0, 1).Select
    For j = 1 To nomf(i + 1)
        ActiveCell.Value = j: ActiveCell.Offset(0, 1).Select
        ActiveCell.Value = mftype(i + 1, j): ActiveCell.Offset(0, 1).Select: ActiveCell.Value = x1(i + 1, j)
        ActiveCell.Offset(0, 1).Select: ActiveCell.Value = x2(i + 1, j): ActiveCell.Offset(0, 1).Select:
        ActiveCell.Value = x3(i + 1, j): ActiveCell.Offset(0, 1).Select:
        ActiveCell.Value = x4(i + 1, j): ActiveCell.Offset(0, 1).Select:
    Next j
Next i
ActiveCell.Value = x3(i + 1, j)
ActiveCell.Offset(0, 1).Select: ActiveCell.Value = x4(i + 1, j): ActiveCell.Offset(1, -3).Select
ActiveCell.Value = y1(i + 1, j): ActiveCell.Offset(0, 1).Select: ActiveCell.Value = y2(i + 1, j)
ActiveCell.Offset(0, 1).Select: ActiveCell.Value = y3(i + 1, j): ActiveCell.Offset(0, 1).Select:
ActiveCell.Value = y4(i + 1, j)
ActiveCell.Offset(1, -5).Select
Next j
ActiveCell.Offset(0, -1).Select
Next i

Call equation
Call rules
Call output
Call defuzzy
Range("I2").Select
End Sub

Sub equation()
    ReDim x(inp - 1) As Single
    ReDim y(inp - 1, k) As Single
    ReDim slope(inp, k) As Single
    Worksheets("data").Select: Range("crispinput").Select
    For i = 1 To inp - 1
        If methodofinp = 1 Then
            x(i) = Val(InputBox("What is the input value of x for variable " & i & " & " & "?", "Fuzzy Inference Program")"
        Else
            x(i) = ActiveCell.Value: ActiveCell.Offset(1, 0).Select
        End If
    Next i
    Worksheets("data1").Activate: Range("Mf1").Select: ActiveCell.Offset(0, 7).Select
    For i = 1 To inp - 1
        For j = 1 To nomf(i)
            If mftype(i, j) = "trian" Then
                If x(i) = x1(i, j) And x(i) = x2(i, j) Then
                    y(i, j) = 1
                ElseIf x(i) = x2(i, j) And x(i) = x3(i, j) Then
                    y(i, j) = 1
                ElseIf x(i) >= x1(i, j) And x(i) <= x2(i, j) Then
                    slope(i, j) = (y2(i, j) - y1(i, j)) / (x2(i, j) - x1(i, j))
                    y(i, j) = slope(i, j) * (x(i) - x1(i, j))
                ElseIf x(i) >= x2(i, j) And x(i) <= x3(i, j) Then
                    slope(i, j) = (y3(i, j) - y2(i, j)) / (x3(i, j) - x2(i, j))
                    y(i, j) = slope(i, j) * (x(i) - x2(i, j)) + y2(i, j)
                Else: y(i, j) = 0
            End If
        Next j
    End Sub
Else
    If x(i) = x1(i, j) And x(i) = x2(i, j) Then
        y(i, j) = 1
    ElseIf x(i) = x3(i, j) And x(i) = x4(i, j) Then
        y(i, j) = 1
    ElseIf x(i) >= x1(i, j) And x(i) <= x2(i, j) Then
        slope(i, j) = (y2(i, j) - y1(i, j)) / (x2(i, j) - x1(i, j))
        y(i, j) = slope(i, j) * (x(i) - x1(i, j))
ElseIf x(i) >= x2(i, j) And x(i) <= x3(i, j) Then
    y(i, j) = 1
ElseIf x(i) >= x3(i, j) And x(i) <= x4(i, j) Then
    slope(i, j) = (y4(i, j) - y3(i, j)) / (x4(i, j) - x3(i, j))
    y(i, j) = slope(i, j) * (x(i) - x3(i, j)) + y3(i, j)
Else: y(i, j) = 0
End If
End If
ActiveCell.Value = x(i): ActiveCell.Offset(0, 1).Select: ActiveCell.Value = y(i, j)
ActiveCell.Offset(2, -1).Select
Next j
Next i
End Sub

Sub rules()
    Worksheets("data").Select: Range("Nrules").Select
    If methodofinp = 1 Then
        nrul = Val(InputBox("What is the total number of rules? ", "Fuzzy Inference Program", "1"))
    Else
        nrul = ActiveCell.Value
    End If
    ReDim connect(nrul) As String
    ReDim v1(nrul), v2(nrul), v3(nrul), v4(nrul), v5(nrul), v6(nrul), v7(nrul) As Integer
    ReDim m1(nrul), m2(nrul), m3(nrul), m4(nrul), m5(nrul), m6(nrul), m7(nrul) As Integer
    ReDim z1(nrul), z2(nrul), z3(nrul), z4(nrul), z5(nrul), z6(nrul), z7(nrul) As Single
    ReDim yfire(nrul) As Single
    ReDim Zmin(nrul), Zmax(nrul) As Single
    ReDim "rule1".Select
    For i = 1 To nrul
        If methodofinp = 1 Then
            DialogSheets("Dialog2").Labels("rule No label").Caption = "Rule " & i
            DialogSheets("Dialog2").Show
            If DialogSheets("Dialog2").OptionButtons("and Option").Value = xlOn Then
                connect(i) = "and"
            End If
        End If
        With DialogSheets("Dialog2")
            v1(i) = Int(.EditBoxes("First Var Edit").Caption)
            v2(i) = Int(.EditBoxes("second Var Edit").Caption)
            v3(i) = Int(.EditBoxes("third Var Edit").Caption)
            v4(i) = Int(.EditBoxes("Fourth Var Edit").Caption)
            v5(i) = Int(.EditBoxes("Fifth Var Edit").Caption)
            v6(i) = Int(.EditBoxes("Sixth Var Edit").Caption)
            v7(i) = Int(.EditBoxes("Seventh Var Edit").Caption)
            m1(i) = Int(.EditBoxes("First mf Edit").Caption)
            m2(i) = Int(.EditBoxes("second mf Edit").Caption)
            m3(i) = Int(.EditBoxes("third mf Edit").Caption)
            m4(i) = Int(.EditBoxes("fourth mf Edit").Caption)
            m5(i) = Int(.EditBoxes("Fifth mf Edit").Caption)
            m6(i) = Int(.EditBoxes("Sixth mf Edit").Caption)
            m7(i) = Int(.EditBoxes("Seventh mf Edit").Caption)
        End With
    Else
        connect(i) = ActiveCell.Value: ActiveCell.Offset(0, 1).Select: v1(i) = ActiveCell.Value
ActiveCell.Offset(0, 1).Select: m1(i) = ActiveCell.Value
ActiveCell.Offset(0, 1).Select: v2(i) = ActiveCell.Value
ActiveCell.Offset(0, 1).Select: m2(i) = ActiveCell.Value
ActiveCell.Offset(0, 1).Select: v3(i) = ActiveCell.Value
ActiveCell.Offset(0, 1).Select: m3(i) = ActiveCell.Value
ActiveCell.Offset(0, 1).Select: v4(i) = ActiveCell.Value
ActiveCell.Offset(0, 1).Select: m4(i) = ActiveCell.Value
ActiveCell.Offset(0, 1).Select: v5(i) = ActiveCell.Value
ActiveCell.Offset(0, 1).Select: m5(i) = ActiveCell.Value
ActiveCell.Offset(0, 1).Select: v6(i) = ActiveCell.Value
ActiveCell.Offset(0, 1).Select: m6(i) = ActiveCell.Value
ActiveCell.Offset(0, 1).Select: v7(i) = ActiveCell.Value
ActiveCell.Offset(0, 1).Select: m7(i) = ActiveCell.Value
End If
ActiveCell.Offset(1, -14).Select
Next i
Worksheets("data1").Activate: Range("Mf1").Select: ActiveCell.Offset(0, 9).Select
Select Case inp
Case 2
For i = 1 To nrul
    z1(i) = y(v1(i), m1(i)): Zmin(i) = z1(i): Zmax(i) = z1(i)
    ActiveCell.Value = i: ActiveCell.Offset(0, 1).Select: ActiveCell.Value = Zmin(i)
    yfire(i) = Zmax(i): yfire(i) = Zmin(i)
    ActiveCell.Offset(1, -1).Select
Next i
Case 3
For i = 1 To nrul
    Zmin(i) = 1: Zmax(i) = 0
    z1(i) = y(v1(i), m1(i)): z2(i) = y(v2(i), m2(i))
    If connect(i) = "and" Then
        If Zmin(i) > z1(i) Then Zmin(i) = z1(i)
        If Zmin(i) > z2(i) Then Zmin(i) = z2(i)
        yfire(i) = Zmin(i)
        ActiveCell.Value = i: ActiveCell.Offset(0, 1).Select: ActiveCell.Value = Zmin(i)
    Else
        If Zmax(i) < z1(i) Then Zmax(i) = z1(i)
        If Zmax(i) < z2(i) Then Zmax(i) = z2(i)
        yfire(i) = Zmax(i)
        ActiveCell.Value = i: ActiveCell.Offset(0, 1).Select: ActiveCell.Value = Zmax(i)
    End If
    ActiveCell.Offset(1, -1).Select
Next i
Case 4
For i = 1 To nrul
    Zmin(i) = 1: Zmax(i) = 0
    z1(i) = y(v1(i), m1(i)): z2(i) = y(v2(i), m2(i)): z3(i) = y(v3(i), m3(i))
    If connect(i) = "and" Then
        If Zmin(i) > z1(i) Then Zmin(i) = z1(i)
        If Zmin(i) > z2(i) Then Zmin(i) = z2(i)
        If Zmin(i) > z3(i) Then Zmin(i) = z3(i)
        yfire(i) = Zmin(i)
        ActiveCell.Value = i: ActiveCell.Offset(0, 1).Select: ActiveCell.Value = Zmin(i)
    Else
        If Zmax(i) < z1(i) Then Zmax(i) = z1(i)
        If Zmax(i) < z2(i) Then Zmax(i) = z2(i)
        If Zmax(i) < z3(i) Then Zmax(i) = z3(i)
        yfire(i) = Zmax(i)
        ActiveCell.Value = i: ActiveCell.Offset(0, 1).Select: ActiveCell.Value = Zmax(i)
    End If
    ActiveCell.Offset(1, -1).Select
Next i
If Zmax(i) < z1(i) Then Zmax(i) = z1(i)
If Zmax(i) < z2(i) Then Zmax(i) = z2(i)
If Zmax(i) < z3(i) Then Zmax(i) = z3(i)
yfire(i) = Zmax(i)
ActiveCell.Value = i: ActiveCell.Offset(0, 1).Select: ActiveCell.Value = Zmax(i)
End If
ActiveCell.Offset(1, -1).Select
Next i
Case 5
For i = 1 To nrul
Zmin(i) = 1: Zmax(i) = 0
z1(i) = y(v1(i), m1(i)): z2(i) = y(v2(i), m2(i)): z3(i) = y(v3(i), m3(i))
z4(i) = y(v4(i), m4(i))
If connect(i) = "and" Then
  If Zmin(i) > z1(i) Then Zmin(i) = z1(i)
  If Zmin(i) > z2(i) Then Zmin(i) = z2(i)
  If Zmin(i) > z3(i) Then Zmin(i) = z3(i)
  If Zmin(i) > z4(i) Then Zmin(i) = z4(i)
yfire(i) = Zmin(i)
ActiveCell.Value = i: ActiveCell.Offset(0, 1).Select: ActiveCell.Value = Zmin(i)
Else
  If Zmax(i) < z1(i) Then Zmax(i) = z1(i)
  If Zmax(i) < z2(i) Then Zmax(i) = z2(i)
  If Zmax(i) < z3(i) Then Zmax(i) = z3(i)
  If Zmax(i) < z4(i) Then Zmax(i) = z4(i)
yfire(i) = Zmax(i)
ActiveCell.Value = i: ActiveCell.Offset(0, 1).Select: ActiveCell.Value = Zmax(i)
End If
ActiveCell.Offset(1, -1).Select
Next i
Case 6
For i = 1 To nrul
Zmin(i) = 1: Zmax(i) = 0
z1(i) = y(v1(i), m1(i)): z2(i) = y(v2(i), m2(i)): z3(i) = y(v3(i), m3(i))
z4(i) = y(v4(i), m4(i)): z5(i) = y(v5(i), m5(i))
If connect(i) = "and" Then
  If Zmin(i) > z1(i) Then Zmin(i) = z1(i)
  If Zmin(i) > z2(i) Then Zmin(i) = z2(i)
  If Zmin(i) > z3(i) Then Zmin(i) = z3(i)
  If Zmin(i) > z4(i) Then Zmin(i) = z4(i)
  If Zmin(i) > z5(i) Then Zmin(i) = z5(i)
yfire(i) = Zmin(i)
ActiveCell.Value = i: ActiveCell.Offset(0, 1).Select: ActiveCell.Value = Zmin(i)
Else
  If Zmax(i) < z1(i) Then Zmax(i) = z1(i)
  If Zmax(i) < z2(i) Then Zmax(i) = z2(i)
  If Zmax(i) < z3(i) Then Zmax(i) = z3(i)
  If Zmax(i) < z4(i) Then Zmax(i) = z4(i)
  If Zmax(i) < z5(i) Then Zmax(i) = z5(i)
yfire(i) = Zmax(i)
ActiveCell.Value = i: ActiveCell.Offset(0, 1).Select: ActiveCell.Value = Zmax(i)
End If
ActiveCell.Offset(1, -1).Select
Case 7
For i = 1 To nrul
    Zmin(i) = 1: Zmax(i) = 0
    z1(i) = y(v1(i), m1(i)): z2(i) = y(v2(i), m2(i)): z3(i) = y(v3(i), m3(i))
    z4(i) = y(v4(i), m4(i)): z5(i) = y(v5(i), m5(i)): z6(i) = y(v6(i), m6(i))
    If connect(i) = "and" Then
        If Zmin(i) > z1(i) Then Zmin(i) = z1(i)
        If Zmin(i) > z2(i) Then Zmin(i) = z2(i)
        If Zmin(i) > z3(i) Then Zmin(i) = z3(i)
        If Zmin(i) > z4(i) Then Zmin(i) = z4(i)
        If Zmin(i) > z5(i) Then Zmin(i) = z5(i)
        If Zmin(i) > z6(i) Then Zmin(i) = z6(i)
        yfire(i) = Zmin(i)
    Else
        If Zmax(i) < z1(i) Then Zmax(i) = z1(i)
        If Zmax(i) < z2(i) Then Zmax(i) = z2(i)
        If Zmax(i) < z3(i) Then Zmax(i) = z3(i)
        If Zmax(i) < z4(i) Then Zmax(i) = z4(i)
        If Zmax(i) < z5(i) Then Zmax(i) = z5(i)
        If Zmax(i) < z6(i) Then Zmax(i) = z6(i)
        yfire(i) = Zmax(i)
    End If
    ActiveCell.Value = i: ActiveCell.Offset(0, 1).Select: ActiveCell.Value = Zmin(i)
Next i
End Select
End Sub

Sub output()
    ReDim x1fir(nrul), x2fir(nrul) As Single
    Dim l As Integer
    Dim p As String
    Dim infrule As String
    l = inp
    If inp = 2 Then r = m2
    If inp = 3 Then r = m3
    If inp = 4 Then r = m4
    If inp = 5 Then r = m5
    If inp = 6 Then r = m6
    If inp = 7 Then r = m7
    Worksheets("data").Select: Range("infrule").Select
    If methodofinp = 1 Then
        DialogSheets("Dialog3").Show
        If DialogSheets("Dialog3").OptionButtons("MaxMin Option").Value = xlOn Then infrule = "MaxMin"
    Else
        infrule = ActiveCell.Value
    End If
    Worksheets("data1").Activate: Range("Mf1").Select: ActiveCell.Offset(0, 11).Select
    For j = 1 To nrul
        If yfire(j) = 0 Then GoTo newrule
        If infrule = "MaxMin" Then
        End If
    Next j
End Sub
If mftype(l, r(j)) = "trian" Then
   x1fir(j) = (x2(l, r(j)) - x1(l, r(j))) * yfire(j) / y2(l, r(j)) + x1(l, r(j))
   x2fir(j) = x3(l, r(j)) - (x3(l, r(j)) - x2(l, r(j))) * yfire(j) / y3(l, r(j))
Else
   x1fir(j) = (x2(l, r(j)) - x1(l, r(j))) * yfire(j) / y2(l, r(j)) + x1(l, r(j))
   x2fir(j) = x4(l, r(j)) - (x4(l, r(j)) - x3(l, r(j))) * yfire(j) / y3(l, r(j))
End If
Else
   If mftype(l, r(j)) = "trian" Then
      x1fir(j) = x2(l, r(j)): x2fir(j) = x2(l, r(j))
   Else
      x1fir(j) = x2(l, r(j)): x2fir(j) = x3(l, r(j))
   End If
End If

newrule:
   ActiveCell.Value = x1fir(j): ActiveCell.Offset(0, 1).Select: ActiveCell.Value = x2fir(j)
ActiveCell.Offset(1, -1).Select
Next j

Worksheets("overallMf").Activate: Range("firring").Select: Range("firring").ClearContents
Range("a1").Select
For i = 1 To nrul
   If yfire(i) = 0 Then GoTo newrul1
      ActiveCell.Value = "Rule " & i: ActiveCell.Offset(1, 0).Select: ActiveCell.Value = "X"
      ActiveCell.Offset(0, 1).Select: ActiveCell.Value = "Y": ActiveCell.Offset(1, -1).Select
      ActiveCell.Value = x1(l, r(i)): ActiveCell.Offset(0, 1).Select: ActiveCell.Value = 0
      ActiveCell.Offset(1, -1).Select: ActiveCell.Value = yfire(i): ActiveCell.Offset(0, 1).Select
      ActiveCell.Value = x2fir(i): ActiveCell.Offset(1, -1).Select: ActiveCell.Value = 0
      If mftype(l, r(i)) = "trian" Then
         ActiveCell.Value = x3(l, r(i)): ActiveCell.Offset(0, 1).Select: ActiveCell.Value = 0
      Else
         ActiveCell.Value = x4(l, r(i)): ActiveCell.Offset(0, 1).Select: ActiveCell.Value = 0
      End If
   End If
   ActiveCell.Offset(-5, 1).Select
newrul1:
   Next i
End Sub

Sub defuzzy()
   Dim ymem() As Single
   Dim Tmoa As Single
   Dim mfuzzy As String
   Dim x1max, x1min As Single
   Dim Yovermax, Xovermax, Xovermin As Single
   l = inp
   If inp = 2 Then r = m2
   If inp = 3 Then r = m3
   If inp = 4 Then r = m4
   If inp = 5 Then r = m5
   If inp = 6 Then r = m6
   If inp = 7 Then r = m7
   x1max = -100000: x1min = 100000
   For i = 1 To nrul
   End Sub
If \( y_{\text{fire}}(i) = 0 \) Then GoTo newrule2
If \( x_1(l, r(i)) < x_{\text{min}} \) Then \( x_{\text{min}} = x_1(l, r(i)) \)
If mftype(l, r(i)) = "trian" Then
  If \( x_3(l, r(i)) > x_{\text{max}} \) Then \( x_{\text{max}} = x_3(l, r(i)) \)
Else
  If \( x_4(l, r(i)) > x_{\text{max}} \) Then \( x_{\text{max}} = x_4(l, r(i)) \)
End If
newrule2:
Next i
If \( x_{\text{max}} = -100000 \) And \( x_{\text{min}} = 100000 \) Then GoTo writefout
Worksheets("data").Select: Range("interval").Select
If methodofinp = 1 Then
  xinter = Val(InputBox("What is the interval value of x for the overall MF variable?", "Fuzzy Inference Program", "0.1"))
Else
  xinter = ActiveCell.Value
End If
s1 = Int((x_{\text{max}} - x_{\text{min}}) / xinter) + 1
ReDim yover(s1) As Single
ReDim xover(s1) As Single
ReDim ymem(nrul) As Single
ReDim aarea(s1) As Single
ReDim moa(s1) As Single
Yovermax = 0
For i = 0 To s1
  xover(i) = x_{\text{min}} + i * xinter
  yover(i) = 0
  For j = 1 To nrul
    If \( y_{\text{fire}}(j) = 0 \) Then GoTo newrule3
    If mftype(l, r(j)) = "trian" Then
      If xover(i) = x_1(l, r(j)) And xover(i) = x_{1\text{fir}}(j) Then
        ymem(j) = y_{\text{fire}}(j)
        If ymem(j) > yover(i) Then yover(i) = ymem(j)
      ElseIf xover(i) = x_3(l, r(j)) And xover(i) = x_{2\text{fir}}(j) Then
        ymem(j) = y_{\text{fire}}(j)
        If ymem(j) > yover(i) Then yover(i) = ymem(j)
      ElseIf xover(i) >= x_1(l, r(j)) And xover(i) <= x_{1\text{fir}}(j) Then
        slope(l, r(j)) = (y_{\text{fire}}(j) - y_{1\text{fir}}(j)) / (x_{1\text{fir}}(j) - x_1(l, r(j)))
        ymem(j) = slope(l, r(j)) * (xover(i) - x_1(l, r(j)))
        If ymem(j) > yover(i) Then yover(i) = ymem(j)
      ElseIf xover(i) >= x_{2\text{fir}}(j) And xover(i) <= x_{3\text{fir}}(j) Then
        slope(l, r(j)) = (y_{3\text{fir}}(j) - y_{\text{fire}}(j)) / (x_{3\text{fir}}(j) - x_{2\text{fir}}(j))
        ymem(j) = slope(l, r(j)) * (xover(i) - x_{2\text{fir}}(j)) + y_{\text{fire}}(j)
        If ymem(j) > yover(i) Then yover(i) = ymem(j)
      Else:
        ymem(j) = 0
      End If
    End If
  End For
End For
If ymem(j) > yover(i) Then yover(i) = ymem(j)
ElseIf xover(i) = x4(l, r(j)) And xover(i) = x2fir(j) Then
  ymem(j) = yfire(j)
  If ymem(j) > yover(i) Then yover(i) = ymem(j)
ElseIf yover(i) = xover(i) And xover(i) <= x1fir(j) Then
  slope(l, r(j)) = (yfire(j) - y1(l, r(j))) / (x1fir(j) - x1(l, r(j)))
  ymem(j) = slope(l, r(j)) * (xover(i) - x1(l, r(j)))
  If ymem(j) > yover(i) Then yover(i) = ymem(j)
ElseIf xover(i) >= x1(l, r(j)) And xover(i) <= x1fir(j) Then
  slope(l, r(j)) = (yfire(j) - y1(l, r(j))) / (x1fir(j) - x1(l, r(j)))
  ymem(j) = slope(l, r(j)) * (xover(i) - x1(l, r(j)))
  If ymem(j) > yover(i) Then yover(i) = ymem(j)
ElseIf xover(i) >= x2fir(j) And xover(i) <= x4(l, r(j)) Then
  slope(l, r(j)) = (y4(l, r(j)) - yfire(j)) / (x4(l, r(j)) - x2fir(j))
  ymem(j) = slope(l, r(j)) * (xover(i) - x2fir(j)) + yfire(j)
  If ymem(j) > yover(i) Then yover(i) = ymem(j)
Else: ymem(j) = 0
End If
End If
newrule3:
Next j
If Yovermax < yover(i) Then Yovermax = yover(i)
Next i
Range("overallmf").ClearContents
Worksheets("overallmf").Activate: Range("a10").Select: ActiveCell.Value = "X"
ActiveCell.Offset(1, 0).Select: ActiveCell.Value = "Y": ActiveCell.Offset(-1, 1).Select
For i = 0 To s1
  ActiveCell.Value = xover(i): ActiveCell.Offset(1, 0).Select: ActiveCell.Value = yover(i)
  ActiveCell.Offset(-1, 1).Select
Next i
Xovermax = -100000: Xovermin = 100000
For i = 1 To s1
  If yover(i) = Yovermax Then
    If Xovermin > xover(i) Then Xovermin = xover(i)
    If Xovermax < xover(i) Then Xovermax = xover(i)
  End If
Next i
Worksheets("data").Select: Range("mdefuzzy").Select
mfuzzy = ActiveCell.Value
If methodofinp = 1 Then
  If DialogSheets("Dialog3").OptionButtons("COA Option").Value = xlOn Then
    TArea = 0: Tmoa = 0
    For i = 1 To s1 - 1
      area(i) = xinter * ((yover(i + 1) + yover(i)) / 2)
      moa(i) = area(i) * (xinter / 2 + xover(i))
      TArea = TArea + area(i)
      Tmoa = Tmoa + moa(i)
    Next i
    fout = Tmoa / TArea
  ElseIf DialogSheets("Dialog3").OptionButtons("MoM Option").Value = xlOn Then
    fout = (Xovermin + Xovermax) / 2
  ElseIf DialogSheets("Dialog3").OptionButtons("LoM Option").Value = xlOn Then
    fout = Xovermax
  Else: fout = Xovermin
Else: fout = Xovermin
End If
Else
    If mfuzzy = "CoA" Then
        TArea = 0: Tmoa = 0
        For i = 1 To sl - 1
            area(i) = xinter * ((yover(i + 1) + yover(i)) / 2)
            moa(i) = area(i) * (xinter / 2 + xover(i))
            TArea = TArea + area(i)
            Tmoa = Tmoa + moa(i)
        Next i
        fout = Tmoa / TArea
    ElseIf mfuzzy = "MoM" Then
        fout = (Xovermin + Xovermax) / 2
    ElseIf mfuzzy = "LoM" Then
        fout = Xovermax
    Else: fout = Xovermin
    End If
Else:
End If
writefout:
    Worksheets("data1").Activate: Range("variable").Select: ActiveCell.Offset(0, 5).Select
    ActiveCell.Value = "Output Crisp Value = ": ActiveCell.Offset(0, 1).Select
    ActiveCell.Value = fout
End Sub
Appendix F: The Solutions Generated by the Genetic Algorithms Program.

Population size= 100

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