A Fuzzy Logic Analysis of Sustainable Concrete Pile Foundations

A Thesis

Presented in Partial Fulfillment of the Requirements for the Degree Master of Science in the Graduate School of The Ohio State University

By

Colleen Emma Atves, B.S.C.E.

Graduate Program in Civil Engineering

The Ohio State University

2010

Thesis Committee:

Fabian Hadipriono Tan, Advisor

William Wolfe

Qian Chen

Abstract

Building foundations are commonly overlooked when it comes to sustainable construction practices. Concrete piles are a major source of carbon dioxide emissions in buildings. In order to determine how sustainable a concrete pile is, several factors must be researched. The use of local or recycled materials or pozzolans helps to make these piles more environmentally conscious. However, since there is not much historical data, it cannot be determined to a definite degree how sustainable the piles are without the use of expert opinions. Variables such as ‘fairly sustainable’ or ‘very unsustainable’ must be utilized to make this determination. These variables are manipulated using fuzzy logic, resulting in imprecise variables like ‘very unsustainable’ to be used.

The thesis presents five different models: Triangular, Translational, Mamdani, Rotational, and Angular. These models are described in detail and the last four are compared to find which model fits best, based on the input variables. The models are presented in C# programming language. The models are used to determine the overall sustainability of a concrete pile construction project.

Dedicated to my Mom and Dad, who have always believed in me.

Acknowledgements

I'd like to thank Dr. Fabian Tan for his jokes, his kind words, and for putting up with me for these past seven years.

I would also like to thank my committee members, Dr. William Wolfe and Dr. Victoria Chen for all for their help in this process.

Lastly, I would like to thank my friends and family for supporting me throughout the years. I am forever in their debt.

Vita

August 1985 ....Born Cleveland, Ohio

2003..North Royalton High School

2008..B.S. Civil Engineering,

The Ohio State University

2008 to 2010...Graduate Teaching Associate,

First Year Engineering Program

The Ohio State University

Fields of Study

Major Field: Civil Engineering

Specialization: Construction Management

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CHAPTER 1 : INTRODUCTION

1.1 Introduction

Green construction has become a way of the industry. People have become obsessed with this 'green craze' and it has invaded just about every aspect of day-to-day life. Construction processes now strive for environmental responsibility as well as the bottom line, making it a more complicated process.

One aspect often ignored in green construction is concrete pile foundations. What makes something sustainable? This is not always clear, varying from person to person, and project to project.

1.2 Objectives of Study

This thesis will attempt to evaluate the sustainability of concrete pile foundations. This evaluation will depend upon user-entered data to make a determination of sustainability. Fuzzy logic will be explained and utilized, and five different models will be implemented and evaluated. A best model will be chosen and examined. These models will be implemented in C# programming language, and will determine a sustainability rating for the user. The end-user does not need to have knowledge of fuzzy logic to run and understand the programs.

1.3 Scope and Limitations

This thesis focuses on a construction project utilizing concrete pile foundations. The materials will be the focus, as well as construction practices. The overall quality, functionality, or other stress/strain qualities of piles in general will not be focused on. The study focuses on the planning stages of the project, and should not be used to evaluate an existing foundation. Additionally, the membership functions utilized in the following models are subjective values. They were not changed from the cited sources and therefore may not be optimal for all applications.

1.4 Research Tasks

The study is broken down into the following four tasks:

1. Research green construction, identify material elements

2. Identify models that will evaluate sustainability

3. Implement each model

4. Compare the models, determine which model fits best

CHAPTER 2 : LITERATURE SEARCH

2.1 Introduction

"With environmental consciousness becoming a way of life, interest in conservation, resource depletion prevention, construction material recycling, and building green is growing" [12]. The decision to 'go green' has become easier over the years, as the economic and social benefits begin to far outweigh the initial cost. Projects that used to focus primarily on reliability, construction efficiency, and cost effectiveness now have new factors to consider. The projects need to be environmentally sensitive in the materials that are used and recycling on site. The must save energy by being more efficient with equipment use, and transportation of materials. Finally, they must conserve natural resources by not building on green fields, but instead use the sites of previously existing structures.

The birth of this green industry has provided the construction business with a plethora of new options in building. Many of these options are included in the Leadership in Energy and Environmental Design (L.E.E.D.) for New Construction Requirements [11]. However, one portion of the building is largely overlooked. Selecting a foundation that is environmentally responsible is often ignored. Since these systems are unseen, their great environmental impacts can go unnoticed. The use of concrete in piles and slabs continues to take place. In addition, steel reinforcements and piles can have great impacts. Attempts need to be made to find alternative methods and materials to bring foundations to the next, ‘green’ level.

2.2 Design Plan

The first step in implementing a green construction project is extensive planning. While this normally includes designers and architects, it needs to include construction managers, contractors, and sub-contractors. While architects may consider the environmental impacts of their designs, construction managers will be able to determine what is possible, and how to responsibly carry out the methods of operation. Using the L.E.E.D. Guidelines for Materials and Resources [11] in Table 2.1, this design plan can be carried out effectively and efficiently.

Materials & Resources

		Points
Prereq 1	Storage & Collection of Recyclables	Required
Credit 1.1	Building Reuse, Maintain 75% of Existing Walls, Floors & Roof	1
Credit 1.2	Building Reuse, Maintain 95% of Existing Walls, Floors & Roof	1
Credit 1.3	Building Reuse, Maintain 50% of Interior Non-Structural Elements	1
Credit 2.1	Construction Waste Management, Divert 50% from Disposal	1
Credit 2.2	Construction Waste Management, Divert 75% from Disposal	1
Credit 3.1	Materials Reuse, 5%	1
Credit 3.2	Materials Reuse, 10%	1
Credit 4.1	Recycled Content, 10% (post-consumer + 1/2 pre-consumer)	1
Credit 4.2	Recycled Content, 20% (post-consumer + 1/2 pre-consumer)	1
Credit 5.1	Regional Materials, 10% Extracted, Processed & Manufactured Regionally	1
Credit 5.2	Regional Materials, 20% Extracted, Processed & Manufactured Regionally	1
Credit 6	Rapidly Renewable Materials	1
Credit 7	Certified Wood	1
		13 Possible

Table 2.1: L.E.E.D. v3.0 New Construction and Major Renovations Materials and Resources Credits [11]

2.3 Site Choice

Site choice is a vital component of green construction. In addition to Brownfield redevelopment sites, which will earn the building LEED points, existing sites must be considered. Reuse of existing foundations can result in savings of time, materials, and environmental impact. If such a site is not available, an environmentally responsible foundation design is a must. While building, the lifecycle of the structure should be kept in mind, and what will happen to the site after destruction. “Building to deconstruct” is a healthy way to achieve this goal.

2.4 Concrete

Concrete is the most widely used structural building material in the United States. In addition to being strong and durable, it is also inexpensive . Unfortunately, concrete is also incredibly harmful to the environment [13]. Habitat disturbances are caused from extraction of cement components, sand, and rock. Cement manufacturing causes toxic air and water emissions. Energy is used in extraction, production, and shipping of cement. Mixing of concrete also requirements a large amount of water and generates alkaline wastewater. Additional precautions must be made to prevent run-off [14].

The main culprit behind concrete’s environmentally unfriendly nature is cement. While concrete is only 9-13% cement, it accounts for roughly 92% of its embodied energy [6]. Approximately one ton of carbon dioxide is released per ton of cement produced, totaling 7-8% of man-made CO_2 emissions [7].

2.5 Pozzolans

Environmentally responsible alternatives to cement have emerged in recent years. These pozzolans, i.e. substances that act like cement when they react with alkaline materials, can reduce energy use and carbon emissions. Sources of pozzolans can include industrial byproducts such as fly ash, silica fume, rice husk ash, and furnace slag [6]. Fly ash, which is residue from coal combustion, is a widely used substitute due to its improved workability, plasticity, and compressive strength. It also decreases porosity and increases durability [7]. The downside to this substitute is an increased curing time. Currently, fly ash makes up only 10-15% of standard mixes. However, it can potentially substitute for 35-60% of cement in many applications [6]. Class C fly ash can completely replace cement in some projects. Another way to improve concrete is air entrapment. The addition of chemical foaming agents such as Neopor blocks, heat and steam, such as with autoclaved aerated blocks, or Aircrete concrete foam will displace concrete. These additives also enhance insulation value, reduce weight and materials costs, and retain the durability and fire-resistance of standard concrete [7].

2.6 Determining Sustainability

There are many different variables that can be used to determine sustainability on a project. Different projects may try to focus on one area or another. Projects in areas with extreme weather may have different goals than those in more arid climates. In this thesis, the author will focus on local, or regional, material use.

Existing methods of determining materials sustainability are lacking when it comes to foundations. L.E.E.D. and Green Globes, which are green building rating systems, look at the building as a whole, rather than focus on each element of the structure [10]. These methods also do not view materials in terms of life cycle analysis, and instead simply give credits for a percentage of recycled or regional (local) materials.

One assessment method that does take into account the life cycle of the material is Building for Environmental and Economic Sustainability (BEES) software. BEES offers an overall performance rating based on weighted values of environmental and economic performance. In addition, the BEES program provides detailed graphs for each environmental impact, such as CO_2 released, helping to pinpoint the weakest aspects of the product [8].

These two methods of evaluation still do not take into account foundations specifically. While the BEES program does involve a life cycle assessment, it does not compare different modifications made to the concrete piles and how sustainable each may be. In addition, the program uses only environmental and economic factors. In some cases, other factors may need to be addressed, such as social issues.

2.7 Fuzzy Logic

With a statistical analysis, historical data are available to be used and manipulated. However, sustainability of piling does not have these databanks of information. In this case expert opinions are taken, usually as a linguistic terms, such as '*fairly sustainable'*, or '*not sustainable*'. Therefore, fuzzy logic is employed to manipulate these linguistic variables.

The next chapters will attempt to evaluate sustainability in concrete piles using linguistic terms. These five models will utilize fuzzy logic, using variables such as practicality and cost to make a determination of sustainability. The best model can be used within a decision-making framework in the design process of a concrete piling project to determine what material modifications can be made in order to increase the sustainability of the project.

CHAPTER 3 : TRIANGULAR MODEL

3.1 Introduction

Fuzzy sets originated in 1965 when Zadeh published his first paper “Fuzzy Sets” [15]. Zadeh used fuzzy sets to translate linguistic expressions into quantitative terms. These terms can be applied as a valuable means designed for describing situations where a result is inexact or imprecise. Words like good, very good, and absolutely good are considered to be fuzzy, since they do not have a crisp quantitative limitation. To change these expressions into quantitative values, each expression will be given a “membership function” within the interval of real numbers [0, 1], called ‘fuzzification’.

3.2 Fuzzy Sustainability

The fuzzy set concept is founded on the nature of humans to interpret things subjectively. These interpretations are inexact in quality, but still meaningful. When talking about sustainability, people have varying opinions of what this means. A linguistic variable many be ‘Very Sustainable’, or ‘Fairly Unsustainable’. These are considered fuzzy sets. In this model, three experts will be used each time. The model is currently limited to only three experts. Each expert will be deciding on the sustainability of a certain material or situation and assign a value to it. The number of years of experience the expert has in the field will also be used in the model. The final result will take the three experts' answers and make a determination of sustainability.

3.3 Fuzzy Set Models

The Triangular Model process is taken from Hadipriono [3].

These fuzzy sets can be generalized by Figure 3.1. 'Excellent', 'Good', and 'Less Than Good' are just three examples of these fuzzy sets.

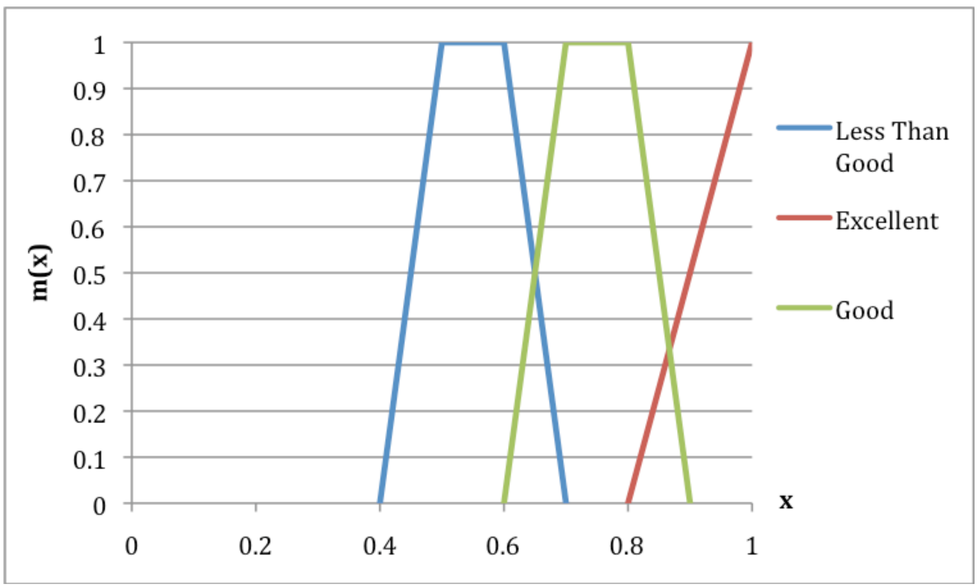


Figure 3.1: Triangular Model – General Fuzzy Set Approximations

In this model slope, peak, and location are used to determine each particular linguistic value. These values are governed by parameters a, b, c, and d, as seen in Figure 3.2. if, for example, the value A is represented by the following fuzzy set: $A = [m_A (x_i) |x]$

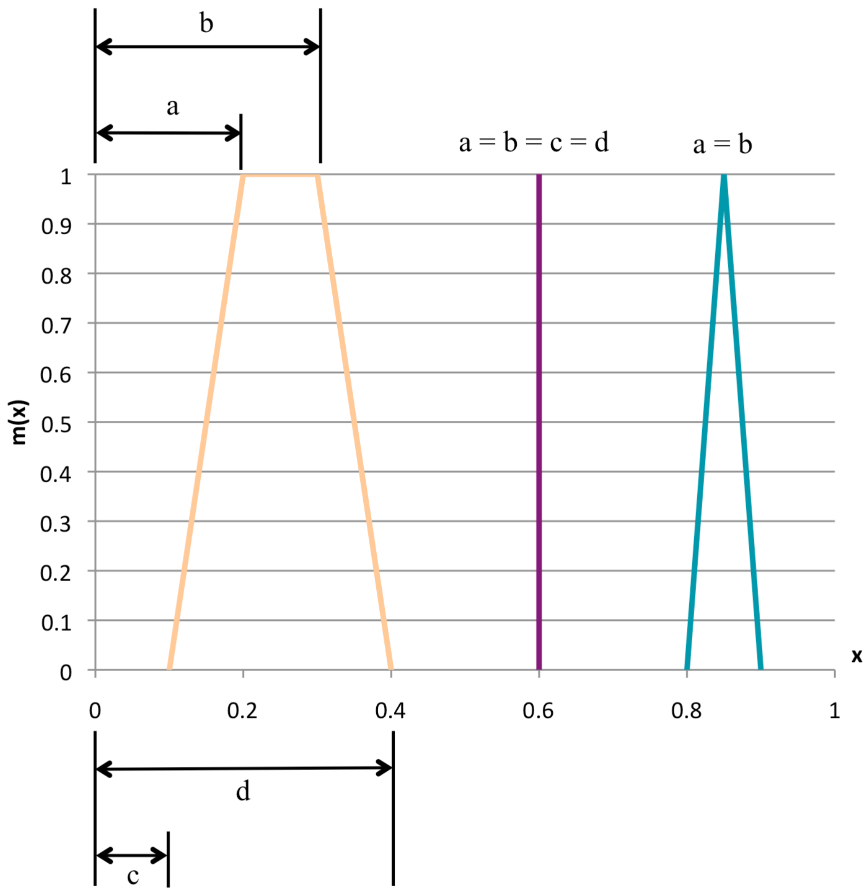


Figure 3.2: Triangular Model – a, b, c, d Values

These values are restricted by the following:

$0 \leq a \leq 1$

$a \leq b \leq 1$

$0 \leq c \leq a$

$b \leq d \leq 1$

Looking at Figure 3.2, if a = b, the model becomes a triangle. If a = b = c = d, the model becomes a straight line, and thus a determined value. In this model, a = b, so triangles will be used, as in Figure 3.3.

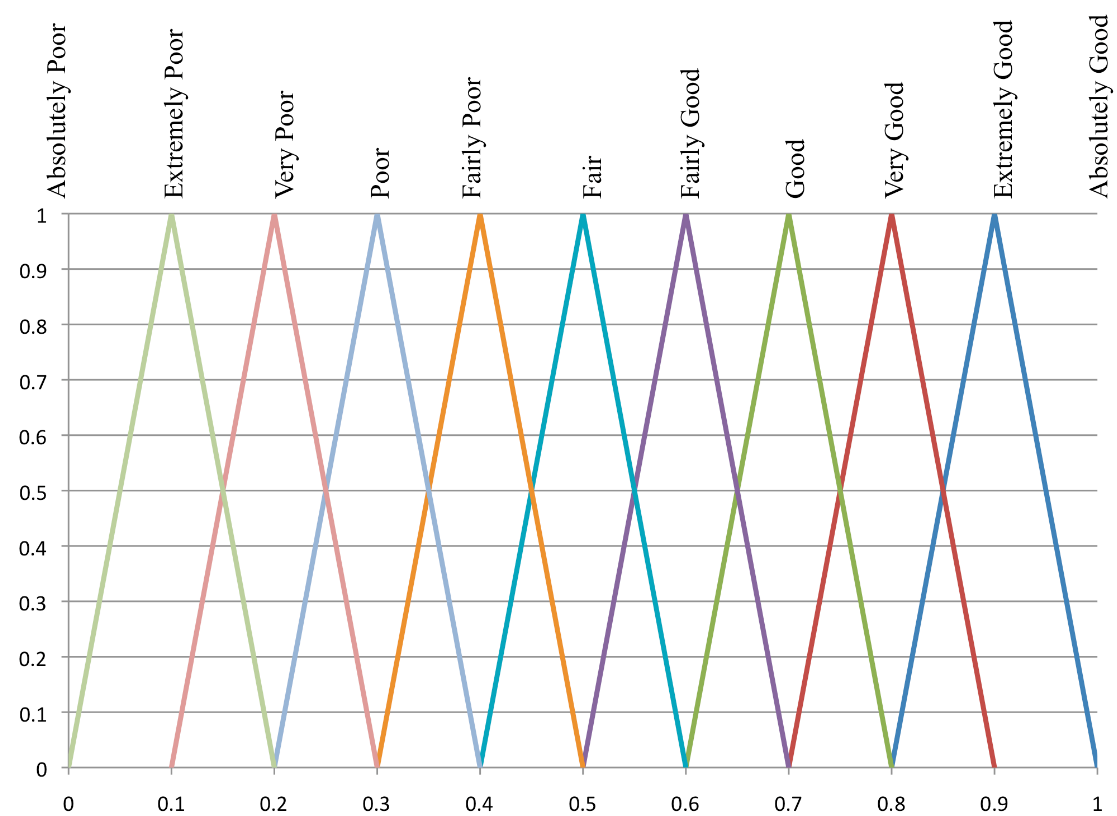


Figure 3.3: Triangular Model - Standard Sustainability Values

While fuzzy sets may have negative, positive, or even neutral characteristics, they are determined by the ranking index that follows:

$$I = Ar - Al + C \tag{3.1}$$

where I is the ranking index; Ar is the area enclosed to the right of the membership function; Al is the area enclosed to the left of the membership function; C is a constant representing the area of the universe of discourse. In this model C = 1.

Expanding the equation for the model ranging from 0 to 1: (3.2-3.3)

$$I = \frac{(1-b) + (1-d)}{2} - \frac{(a+c)}{2} + 1$$

$$= 2 - \frac{(a+b+c+d)}{2}$$

In order to find the overall rating of the three experts, the following equation must be implemented: (3.4)

$$R_T = \frac{\sum (R_i \times W_i)}{\sum Wi}$$

where R_T is the overall rating; R_i is the individual rating; W_i is the weight of a particular rating. In this model, W_i refers to the number of years the expert has been in the field.

3.4 Example of Triangular Model

A hypothetical example of this model is as follows:

The first expert, with 6 years of experience, gives a sustainability rating of 7-8. The second expert, with 6-7 years of experience, gives a sustainability rating of 7-9. Finally, the third expert, with 7 years of experience, gives a sustainability rating of 8-9.

$$R_{TL} = \frac{[\,(0.7 \times 0.6) + (0.7 \times 0.6) + (0.8 \times 0.7)\,]}{[\,0.6 + 0.6 + 0.7\,]}$$

$$R_{TR} = \frac{[(0.8 \times 0.6) + (0.9 \times 0.7) + (0.9 \times 0.7)\,]}{[0.6 + 0.7 + 0.7]}$$

$$= [0.74, 0.87]$$

Figure 3.4 illustrates the three experts' choices as R_1, R_2, and R_3. Figure 3.5 gives the final R_T.

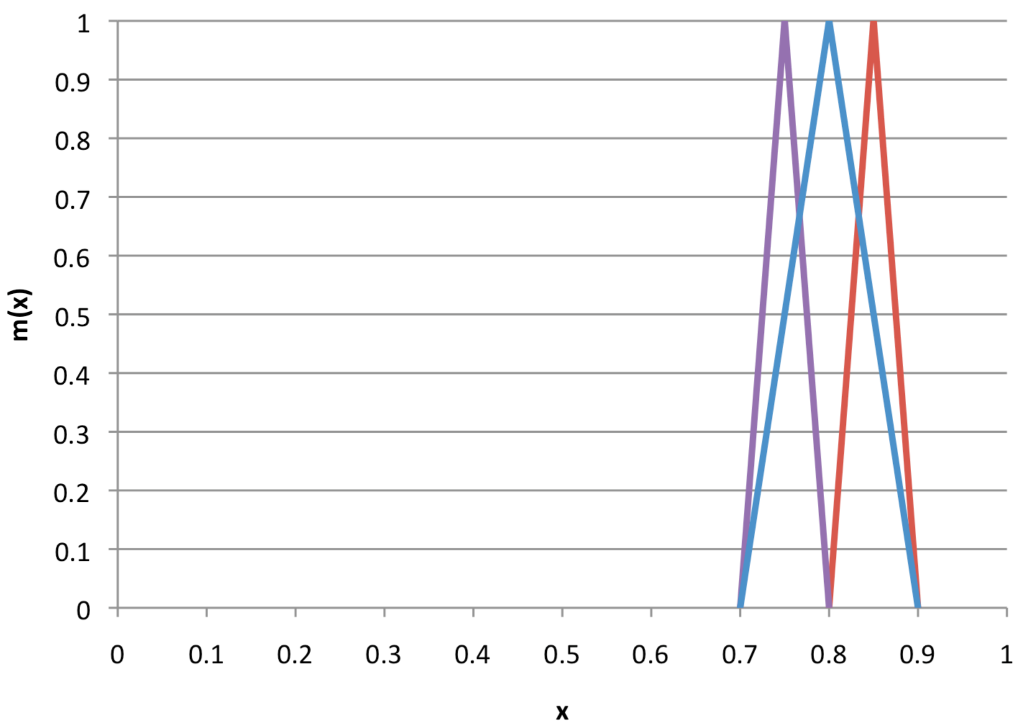


Figure 3.4: Triangular Model - R_1, R_2, R_3 Expert Input

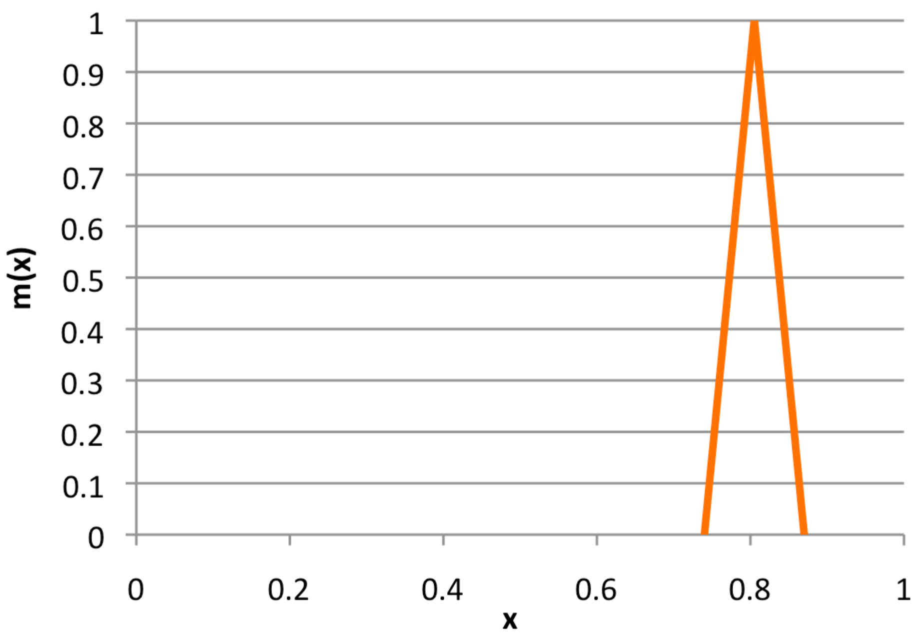


Figure 3.5: Triangular Model - R_T

To determine I, we use the values from R_T:

$R_{T1} = c$; $R_{T2} = d$;

$a = b = (R_{T1}+R_{T2})/2$

Therefore:

$$I = 2 - \frac{(a+b+c+d)}{2}$$

$$= 2 - \frac{(0.805+0.805+0.74+0.87)}{2}$$

$$= 0.39$$

Based on Figure 3.5, and using Figure 3.3 as a reference, the sustainability ranking lies between ‘very good’ and ‘extremely good’. Since I = 0.39, it is closer to ‘very good’.

3.5 Software Program

A computer software program was built in order to run the Triangular Model. There are four drop-down boxes for each expert. The expert will enter a range of years of experience, and what the sustainability rating is (Figure 3.6).

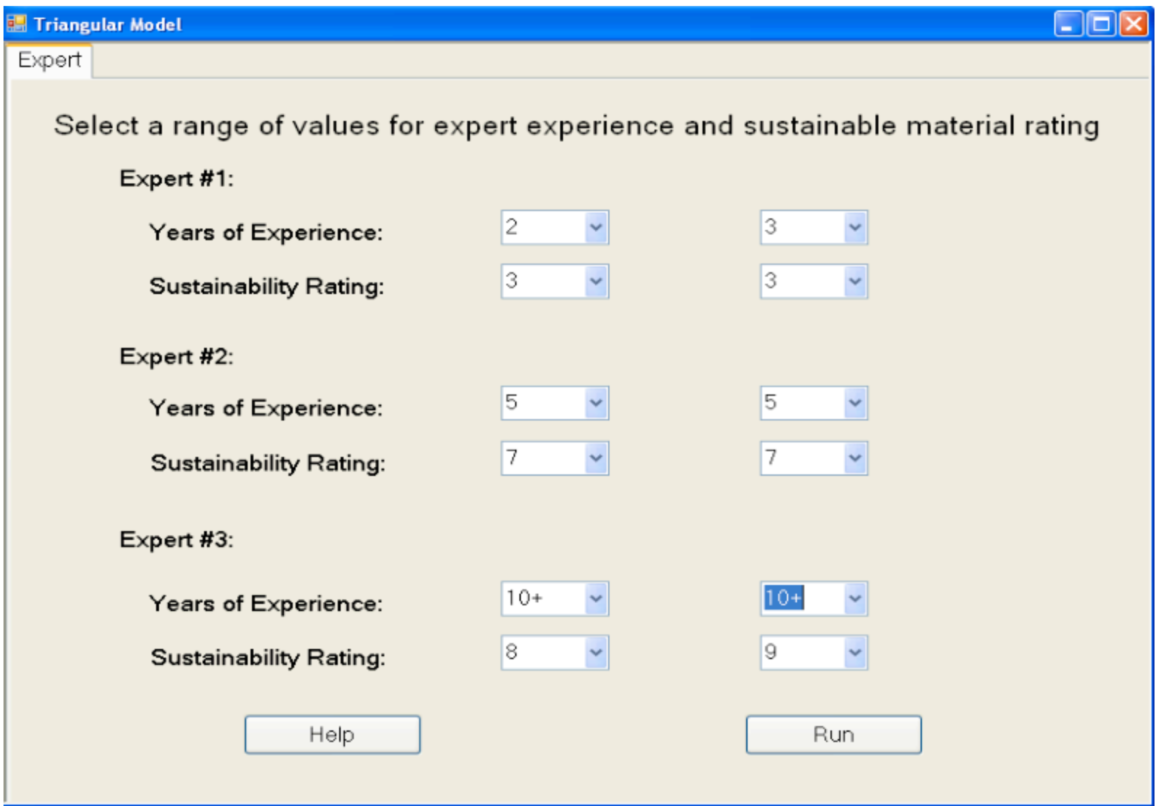


Figure 3.6: Triangular Model Program - Expert Input

If there is any confusion as to what these variables are referring to, the user may access the help box (Figure 3.7), which will explain the variables to them.

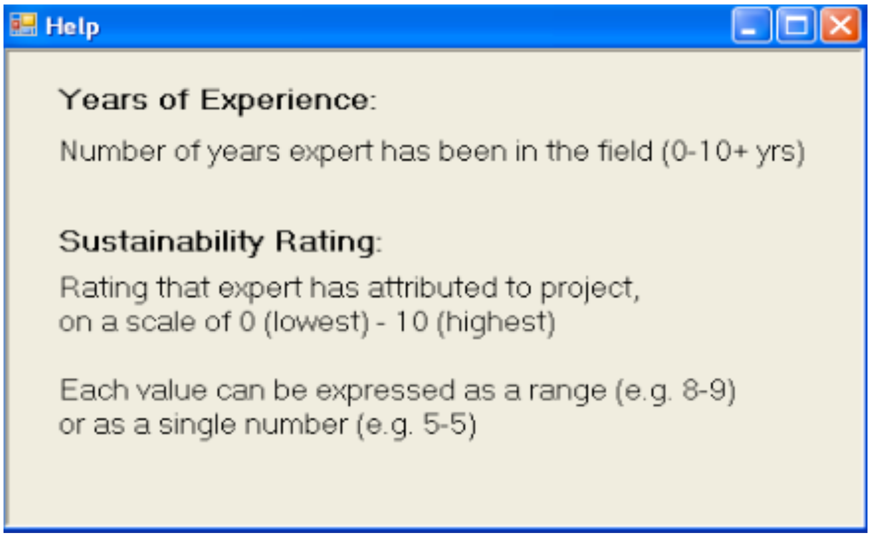


Figure 3.7: Triangular Model Program – Help Screen

After the user has entered the experts' data, there will be a graphical, numerical, and linguistic output, as in Figure 3.8. The graph displays R_1, R_2, and R_3 in light blue, and the final R_T value in bold red. The R_T range is also given (in this case [0.71, 0.74]). Additionally, the I value is calculated (0.54). Lastly, a linguistic output is given, to defuzzify the process. Here the sustainability is 'Good'.

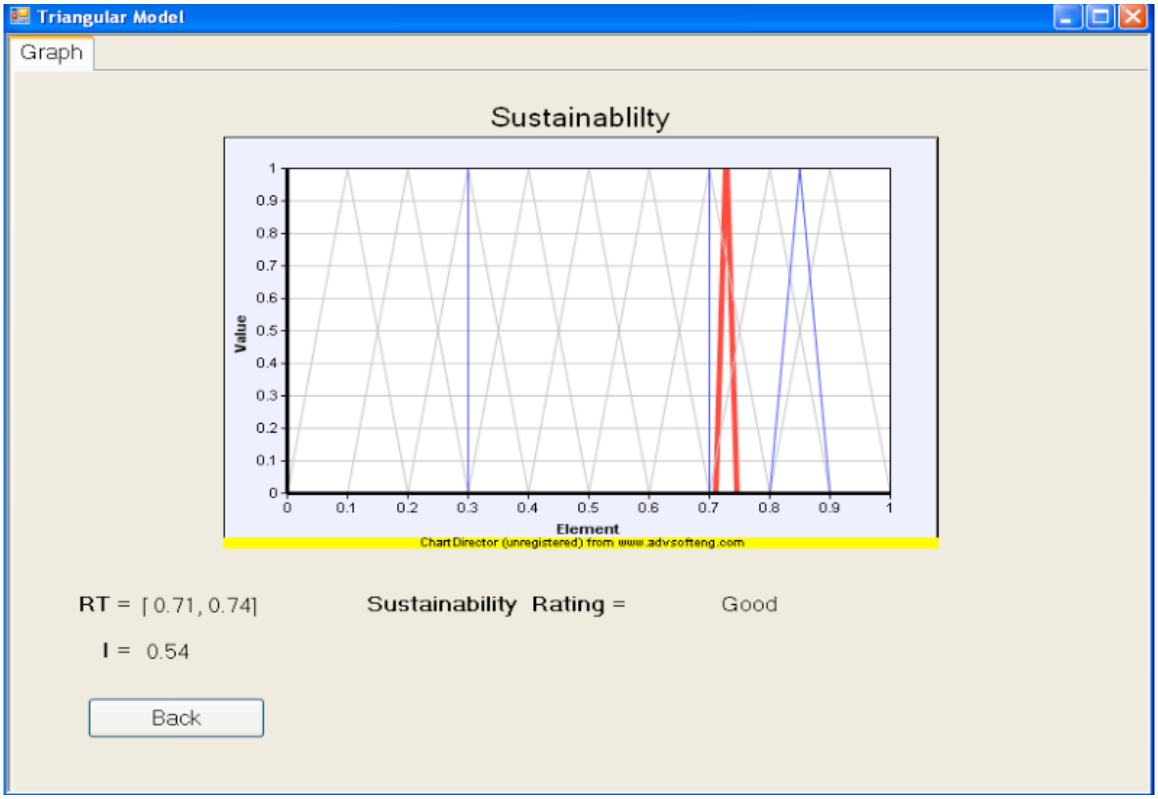


Figure 3.8: Triangular Model Program - Output

Looking at the graph, the straight line on the left is associated with Expert #1, who had the least amount of experience. The other two experts rated the sustainability higher, and also had more experience. This pulled the final graph towards the right, and a more positive sustainability.

Additional examples of the Triangular Model can be found in Appendix A.

CHAPTER 4 : TRANSLATIONAL MODEL

4.1 Introduction

This chapter discusses the use of fuzzy set triangular model to convert linguistic expressions into numerical sets. The translational model of the fuzzy set concept is applied in this chapter. Six inputs will be assigned to the model, dealing with both the practicality and cost effectiveness of trying to make the concrete piling project more sustainable.

4.2 Events

The Translational Model process is taken from Hadipriono [2].

The events used in the model have been simplified using symbols ‘A’ and ‘B’, in Table 4.1 and Table 4.2.

Symbol	Type
A1:	*Recycle Waste*
	Recycling any waste products produced during construction
A2:	*Reuse Existing Materials*
	Existing materials from previous structures, such as old concrete
A3:	*Divert Reusable Materials*
	Any materials that can be reused in other projects, such as pre-existing structure elements.

Table 4.1: Translational Model Events - Jobsite Modifications

Symbol	Type
B1:	*Recycled Materials*
	Materials in the concrete mix, such as aggregate.
B2:	*Local Materials*
	Materials taken from local suppliers, reducing transportation costs and environmental effects.
B3:	*Pozzolans*
	Environmentally conscious substitutes for cement in a concrete mix.

Table 4.2: Translational Model Events - Material Modifications

4.3 Linguistic Values for Variables

The sustainability of the concrete pile construction depends on the practicality of different sustainable jobsite modifications, and the cost of modifications to the concrete. The sustainability will be represented by the following linguistic terms:

- Very Sustainable
- Sustainable
- Moderate
- Unsustainable
- Very Unsustainable

The rules in Table 4.3 and Table 4.4 show the relationship between practicality vs. consequence, and cost vs. consequence. The practicality ranges from *very poor (VP)* to *very good (VG)*. A *very poor (VP)* practicality would result in a consequence of *very negative (VN)*. The cost also ranges from *very poor (VP)* to *very good (VG)*. A *very good (VG)* cost means that the cost is low.

Consequence	*Practicality*				
	Very Poor (VP)	Poor (P)	Fair (F)	Good (G)	Very Good (VG)
Very Negative (VN)	A1, A2, A3				
Negative (N)		A1, A2, A3			
Moderate (M)			A1, A2, A3		
Positive (P)				A1, A2, A3	
Very Positive (VP)					A1, A2, A3

Table 4.3: Translational Model - Practicality of Jobsite Modifications vs. Consequence

Consequence	*Cost*				
	Very Poor (VP)	Poor (P)	Fair (F)	Good (G)	Very Good (VG)
Very Negative (VN)	A1, A2, A3				
Negative (N)		A1, A2, A3			
Moderate (M)			A1, A2, A3		
Positive (P)				A1, A2, A3	
Very Positive (VP)					A1, A2, A3

Table 4.4: Translational Model - Cost of Material Modifications vs. Consequence

These rules were formulated by the author. However, given more information from experts in the field, they may be altered to give a more accurate relation.

These linguistic values must be interpreted as fuzzy sets. Table 4.5 shows the values being used in this model. These values were taken from Hadipriono [2]. Changing these values in this model is beyond the scope of study.

Practicality	*Cost*	*Consequence*	*Values*
Very Poor (VP)	Very High (VH)	Very Negative (VN)	[0/1, 0.1/0.81, 0.2/0.36]
Poor (P)	High (H)	Negative (N)	[0/1, 0.1/0.9, 0.2/0.6]
Fair (F)	Average (A)	Moderate (M)	[0.3/0.6, 0.4/0.9, 0.5/1, 0.6/0.9, 0.7/0.6]
Good (G)	Low (L)	Positive (P)	[0.8/0.6, 0.9/0.9, 1/1]
Very Good (VG)	Very Low (VL)	Very Positive (VP)	[0.8/0.36, 0.9/0.81, 1/1]

Table 4.5: Translational Model - Fuzzy Set Values for Practicality, Cost, and Consequence

4.4 Manipulating Membership Functions

Since the linguistic variables Practicality and Consequence are in different universes of discourse, a fuzzy relation is needed to associate their fuzzy set values. RP1, for example, is the membership function relation between fuzzy subsets Very Poor (VP) and

Very Negative (VN), from Table 4.6. The relation for practicality (RP1) can be found by using the equation:

$$f_{RP1}(x,y) = f_{VNxVP}(x,y)$$

$$= \wedge\, [f_{VP}(x_i), f_{VN}(y_j)] \qquad x\ \varepsilon\ X;\ \forall\ y\ \varepsilon\ Y \qquad (4.1)$$

where VP ⊂ X and VN ⊂ Y; X and Y are universes of Practicality and Consequence, respectively; "∧" denotes the conjunction, or intersection.

Jobsite Modifications	*Practicality*	*Consequence*
Recycle Waste (A1)	Very Poor (VP)	Very Negative (VN)
Reuse Existing Materials (A2)	Fair (F)	Moderate (M)
Divert Reusable Materials (A3)	Very Good (VG)	Very Positive (VP)

Table 4.6: Translational Model - Practicality vs. Consequence

This equation yields RP1 in Table 4.7:

						Practicality: Very Negative (VN)						
RP1 =		**0**	**0.1**	**0.2**	**0.3**	**0.4**	**0.5**	**0.6**	**0.7**	**0.8**	**0.9**	**1**
VN x VF	**0**	1	0.81	0.36	0	0	0	0	0	0	0	0
	0.1	0.81	0.81	0.36	0	0	0	0	0	0	0	0
	0.2	0.36	0.36	0.36	0	0	0	0	0	0	0	0
	0.3	0	0	0	0	0	0	0	0	0	0	0
Conseq:	**0.4**	0	0	0	0	0	0	0	0	0	0	0
Very Poor	**0.5**	0	0	0	0	0	0	0	0	0	0	0
(VP)	**0.6**	0	0	0	0	0	0	0	0	0	0	0
	0.7	0	0	0	0	0	0	0	0	0	0	0
	0.8	0	0	0	0	0	0	0	0	0	0	0
	0.9	0	0	0	0	0	0	0	0	0	0	0
	1	0	0	0	0	0	0	0	0	0	0	0

Table 4.7: Translational Model - Relation for Practicality 1 (RP1) Matrix

The same equation is used to determine the membership values for RP2 and RP3, as listed in Table 4.6. This equation is also used to determine the membership values of the relations between the fuzzy set values (RC) contained in Cost and Consequence, as listed in Table 4.8. RC2 is seen in Table 4.9. In this case ‘Z’ is the universe of Cost. RC2 is represented by Table 4.9.

Material Modifications	*Cost*	*Consequence*
Recycled Materials (B1)	Very High (VH)	Very Negative (VN)
Local Materials (B2)	High (H)	Negative (N)
Pozzolans (B3)	Average (A)	Moderate (M)

Table 4.8: Translational Model - Cost vs. Consequence

							Conseq: Negative (N)					
RC2 =		**0**	**0.1**	**0.2**	**0.3**	**0.4**	**0.5**	**0.6**	**0.7**	**0.8**	**0.9**	**1**
N x H	0	1	0.9	0.6	0	0	0	0	0	0	0	0
	0.1	0.9	0.9	0.6	0	0	0	0	0	0	0	0
	0.2	0.6	0.6	0.6	0	0	0	0	0	0	0	0
	0.3	0	0	0	0	0	0	0	0	0	0	0
Cost:	**0.4**	0	0	0	0	0	0	0	0	0	0	0
High (H)	**0.5**	0	0	0	0	0	0	0	0	0	0	0
	0.6	0	0	0	0	0	0	0	0	0	0	0
	0.7	0	0	0	0	0	0	0	0	0	0	0
	0.8	0	0	0	0	0	0	0	0	0	0	0
	0.9	0	0	0	0	0	0	0	0	0	0	0
	1	0	0	0	0	0	0	0	0	0	0	0

Table 4.9: Translational Model - Relation for Cost 2 (RC2) Matrix

The membership function of the total relation of RP and RC, is obtained using the following equations: (4.2)

$$f_{\bigvee_{k=1}^{n} RP_k}(x_i, y_j) = \bigvee_{k=1}^{n} [\, f_{RP_k}(x_i, y_j) \,] \qquad f_{\bigvee_{k=1}^{n} RC_k}(x_i, y_j) = \bigvee_{k=1}^{n} [\, f_{RC_k}(x_i, y_j) \,]$$

where $\vee$ denotes the disjunction. In essence, RP takes the minimum of each column of RP1, RP2, and RP3. RC takes the minimum of column of RC1, RC2, and RC3. This gives RP (Table 4.10) and RC (Table 4.11).

		Practicality (P)										
RP =		**0**	**0.1**	**0.2**	**0.3**	**0.4**	**0.5**	**0.6**	**0.7**	**0.8**	**0.9**	**1**
CE x P	**0**	1	0.81	0.36	0	0	0	0	0	0	0	0
	0.1	0.81	0.81	0.36	0	0	0	0	0	0	0	0
	0.2	0.36	0.36	0.36	0	0	0	0	0	0	0	0
	0.3	0	0	0	0.6	0.6	0.6	0.6	0.6	0	0	0
Conseq	**0.4**	0	0	0	0.6	0.9	0.9	0.9	0.6	0	0	0
(CE)	**0.5**	0	0	0	0.6	0.9	1	0.9	0.6	0	0	0
	0.6	0	0	0	0.6	0.9	0.9	0.9	0.6	0	0	0
	0.7	0	0	0	0.6	0.6	0.6	0.6	0.6	0	0	0
	0.8	0	0	0	0	0	0	0	0	0.36	0.36	0.36
	0.9	0	0	0	0	0	0	0	0	0.36	0.81	0.81
	1	0	0	0	0	0	0	0	0	0.36	0.81	1

Table 4.10: Translational Model - Relation for Practicality (RP) Matrix

		Consequence (CE)										
RC =		**0**	**0.1**	**0.2**	**0.3**	**0.4**	**0.5**	**0.6**	**0.7**	**0.8**	**0.9**	**1**
CE x C	**0**	1	0.9	0.6	0	0	0	0	0	0	0	0
	0.1	0.9	0.9	0.6	0	0	0	0	0	0	0	0
	0.2	0.6	0.6	0.6	0	0	0	0	0	0	0	0
	0.3	0	0	0	0.6	0.6	0.6	0.6	0.6	0	0	0
Cost	**0.4**	0	0	0	0.6	0.9	0.9	0.9	0.6	0	0	0
(C)	**0.5**	0	0	0	0.6	0.9	1	0.9	0.6	0	0	0
	0.6	0	0	0	0.6	0.9	0.9	0.9	0.6	0	0	0
	0.7	0	0	0	0.6	0.6	0.6	0.6	0.6	0	0	0
	0.8	0	0	0	0	0	0	0	0	0	0	0
	0.9	0	0	0	0	0	0	0	0	0	0	0
	1	0	0	0	0	0	0	0	0	0	0	0

Table 4.11: Translational Model - Relation for Cost (RC) Matrix

As seen in the previous equations, RP and RC are not in the same universe of discourse. In order to integrate the two, a fuzzy composition must be performed in which RP and RC are extended into $X \times Y \times Z$, which is a common space. This is done by repeating membership values of RC so $RC^* \subset X \times Y \times Z$.

The membership function of RC o RP is:

$$f_{RC \circ RP}(x_i, z_k) = \vee_y [f_{RC*}(x_i, y_j, z_k) \wedge f_{RP*}(x_i, y_j, z_k)] \quad (4.3)$$

Essentially, this process becomes:

$$f_{RC \circ RP}(x_i, z_k) = \vee_y [f_{RC}(z_k, y_j) \wedge f_{RP}(y_j, x_i)] \quad (4.4)$$

which in essence involves multiplying RP x RT such that "Consequence" is cancelled out, as in Table 4.12.

RT o RE		Practicality (P)										
		0	**0.1**	**0.2**	**0.3**	**0.4**	**0.5**	**0.6**	**0.7**	**0.8**	**0.9**	**1**
	0	1	0.81	0.36	0	0	0	0	0	0	0	0
	0.1	0.9	0.81	0.36	0	0	0	0	0	0	0	0
	0.2	0.6	0.6	0.36	0	0	0	0	0	0	0	0
	0.3	0	0	0	0.6	0.6	0.6	0.6	0.6	0	0	0
Cost	**0.4**	0	0	0	0.6	0.9	0.9	0.9	0.6	0	0	0
(C)	**0.5**	0	0	0	0.6	0.9	1	0.9	0.6	0	0	0
	0.6	0	0	0	0.6	0.9	0.9	0.9	0.6	0	0	0
	0.7	0	0	0	0.6	0.6	0.6	0.6	0.6	0	0	0
	0.8	0	0	0	0	0	0	0	0	0	0	0
	0.9	0	0	0	0	0	0	0	0	0	0	0
	1	0	0	0	0	0	0	0	0	0	0	0

Table 4.12: Translational Model – Fuzzy Composition (RT o RE) Matrix

Finally, in order to obtain the overall sustainability, the membership values from Table 4.12 are projected to the performance space X using the equation:

$$f_{Tx}(x_i) = \vee\, f_{RT \text{ o } RE}\,(x_i, z_k) \tag{4.5}$$

where Tx is the projection of the membership values on the performance space, X. In this projection, the largest value in each column of Table 4.12 is chosen. This gives the final sustainability membership values as:

Tx = [0/1, 0.1/0.81, 0.2/0.36, 0.3/0.6, 0.4/0.9, 0.5/1, 0.6/0.9, 0.7/0.6, 0.8/0, 0.9/0, 1/0]

which is represented graphically by Figure 4.1.

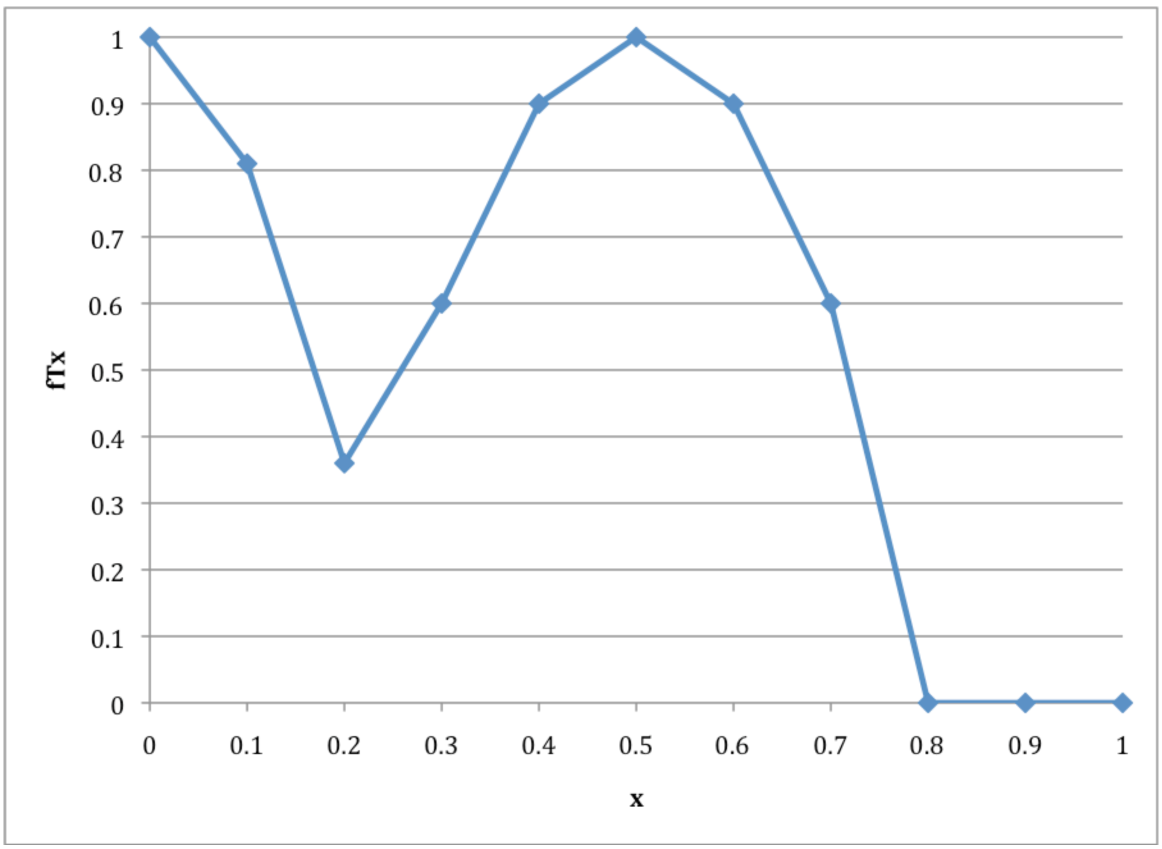


Figure 4.1: Translational Model – Sustainability Membership Values Graph

This graph must be interpreted by the user. Generally, as the line trends towards the right, the sustainability improves. Alternatively, trending left correlates to an unsustainable project. In this example, the result would be a range of sustainability from 'Moderate' to 'Very Unsustainable'.

4.5. Software Program

A software program has been written to allow users (engineers, construction managers, experts) to evaluate the project by inputting linguistic values for the six variables for practicality and cost. In
Figure 4.2, the user evaluates the project using drop-down boxes.

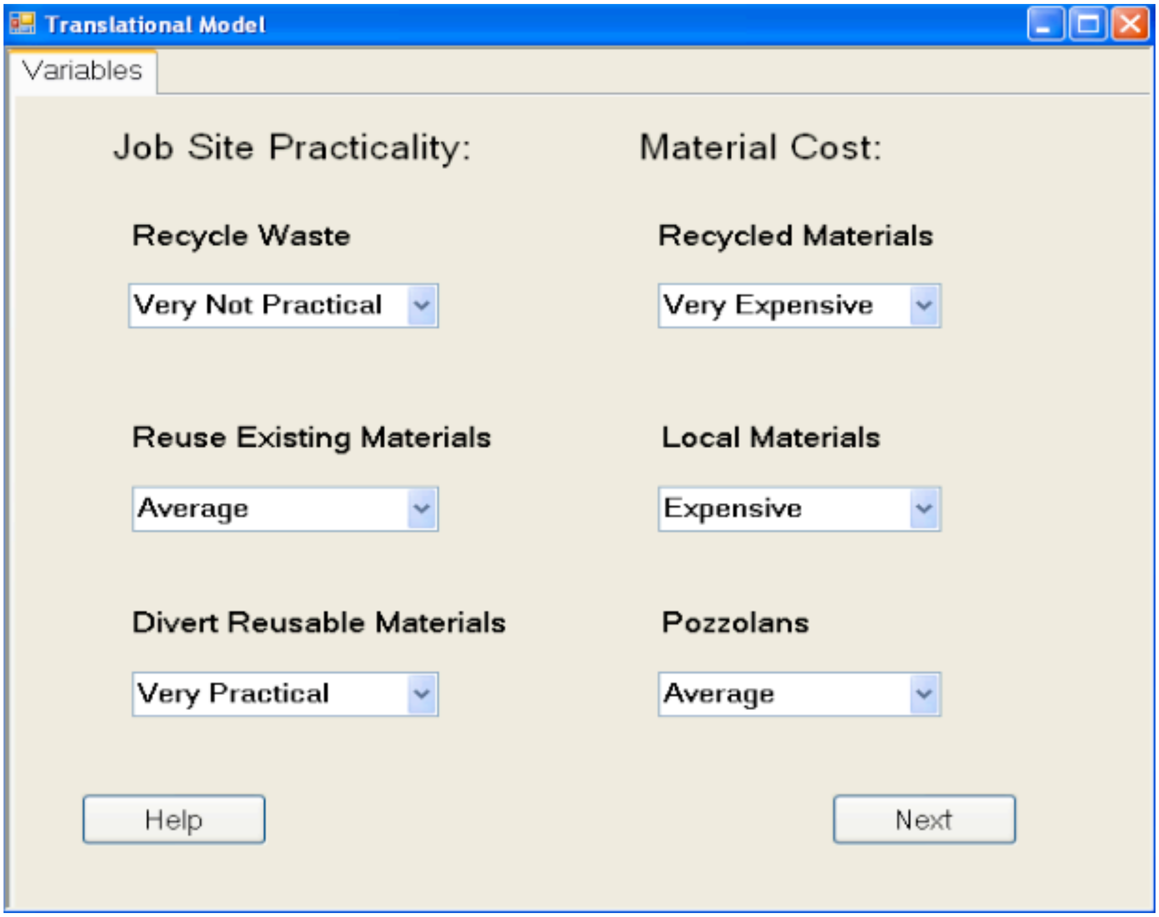


Figure 4.2: Translational Model Program - User Input

If the user has trouble understanding the variables present, the 'Help' button can be pressed, bringing up the Help window, Figure 4.3, which describes the variables.

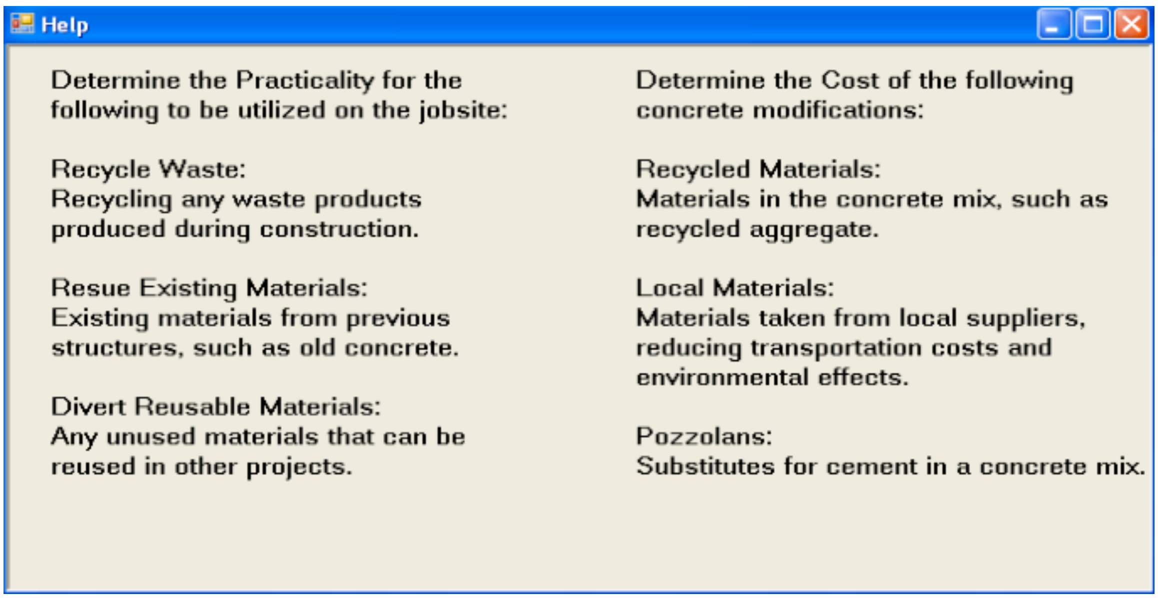
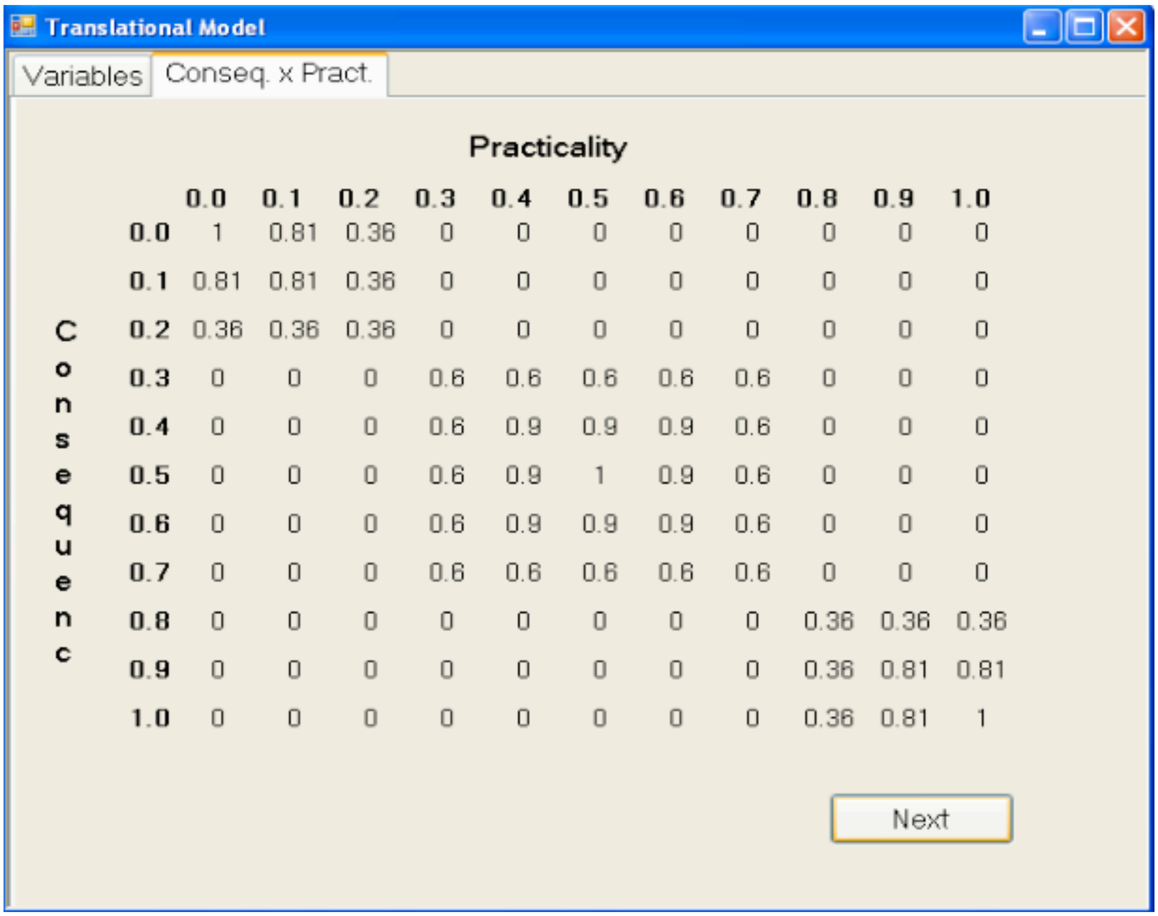


Figure 4.3: Translational Model Program - Help Screen

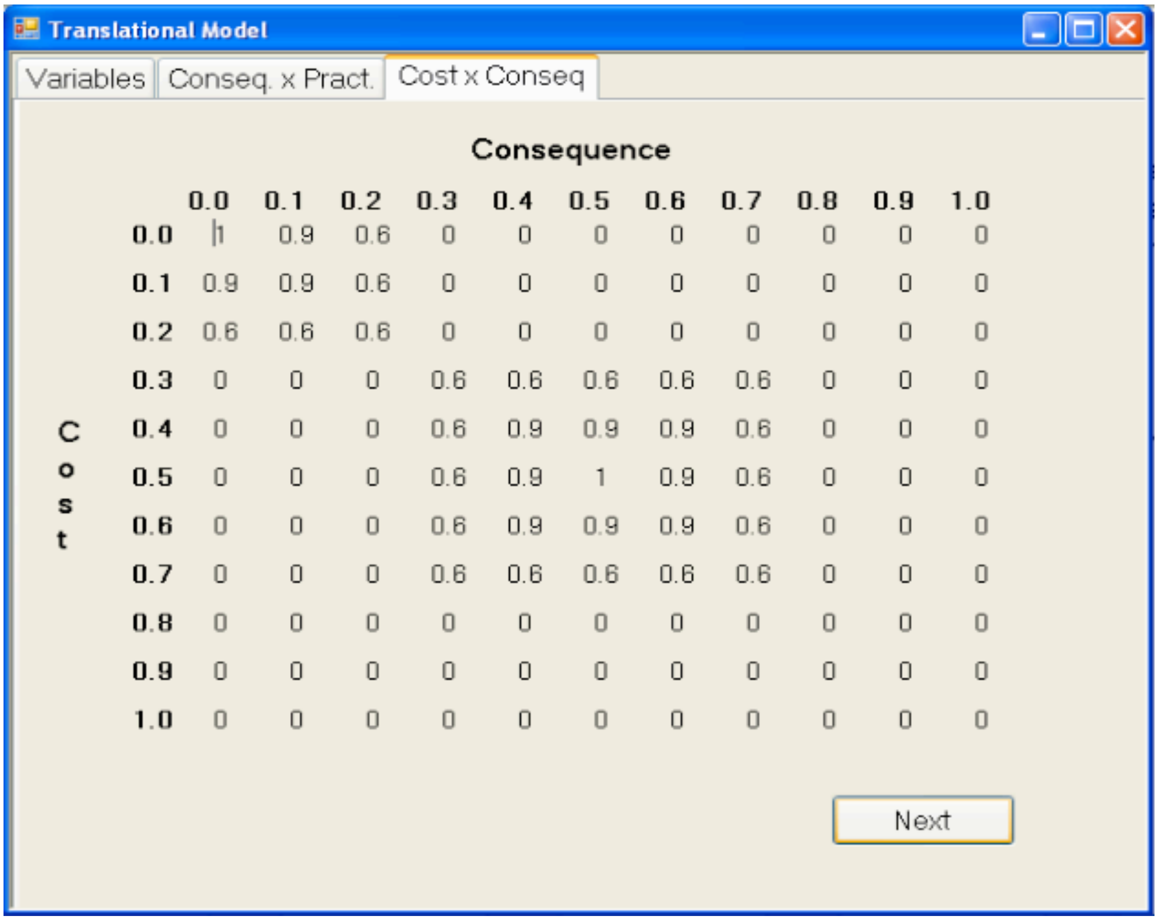
Once the user has inputted the six variables, the ‘Next’ button will be pressed, displaying the matrix ‘Consequence vs. Practicality (RE)’, Figure 4.4.



	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
0.0	1	0.81	0.36	0	0	0	0	0	0	0	0
0.1	0.81	0.81	0.36	0	0	0	0	0	0	0	0
0.2	0.36	0.36	0.36	0	0	0	0	0	0	0	0
0.3	0	0	0	0.6	0.6	0.6	0.6	0.6	0	0	0
0.4	0	0	0	0.6	0.9	0.9	0.9	0.6	0	0	0
0.5	0	0	0	0.6	0.9	1	0.9	0.6	0	0	0
0.6	0	0	0	0.6	0.9	0.9	0.9	0.6	0	0	0
0.7	0	0	0	0.6	0.6	0.6	0.6	0.6	0	0	0
0.8	0	0	0	0	0	0	0	0	0.36	0.36	0.36
0.9	0	0	0	0	0	0	0	0	0.36	0.81	0.81
1.0	0	0	0	0	0	0	0	0	0.36	0.81	1

Figure 4.4: Translational Model Program- Consequence vs. Practicality Matrix

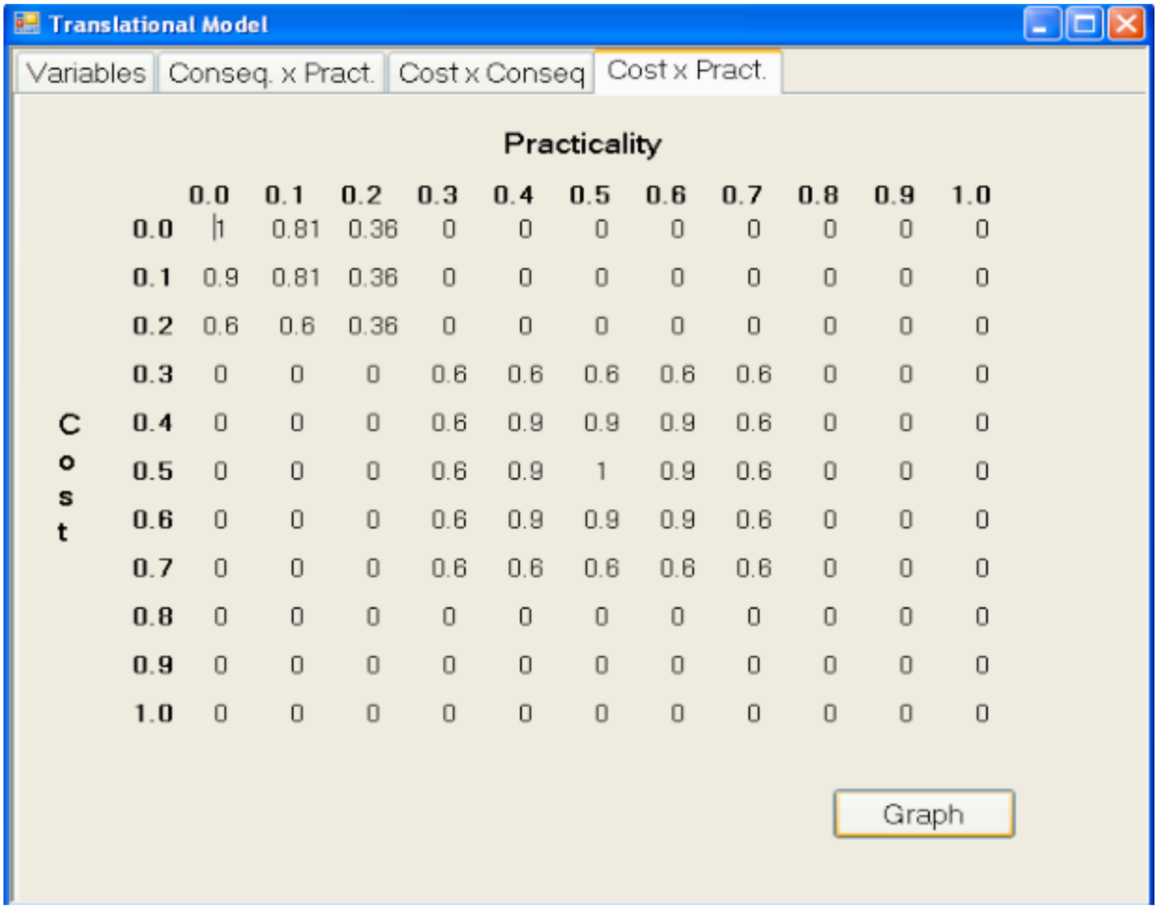
Second, the matrix ‘Cost vs. Consequence’ (RT) is displayed in Figure 4.5.



Cost \ Consequence	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
0.0	1	0.9	0.6	0	0	0	0	0	0	0	0
0.1	0.9	0.9	0.6	0	0	0	0	0	0	0	0
0.2	0.6	0.6	0.6	0	0	0	0	0	0	0	0
0.3	0	0	0	0.6	0.6	0.6	0.6	0.6	0	0	0
0.4	0	0	0	0.6	0.9	0.9	0.9	0.6	0	0	0
0.5	0	0	0	0.6	0.9	1	0.9	0.6	0	0	0
0.6	0	0	0	0.6	0.9	0.9	0.9	0.6	0	0	0
0.7	0	0	0	0.6	0.6	0.6	0.6	0.6	0	0	0
0.8	0	0	0	0	0	0	0	0	0	0	0
0.9	0	0	0	0	0	0	0	0	0	0	0
1.0	0	0	0	0	0	0	0	0	0	0	0

Figure 4.5: Translational Model Program- Cost vs. Consequence Matrix

Third, the matrix ‘Cost vs. Practicality ’ (RT o RE) is displayed in Figure 4.6.



Cost \ Practicality	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
0.0	1	0.81	0.36	0	0	0	0	0	0	0	0
0.1	0.9	0.81	0.36	0	0	0	0	0	0	0	0
0.2	0.6	0.6	0.36	0	0	0	0	0	0	0	0
0.3	0	0	0	0.6	0.6	0.6	0.6	0.6	0	0	0
0.4	0	0	0	0.6	0.9	0.9	0.9	0.6	0	0	0
0.5	0	0	0	0.6	0.9	1	0.9	0.6	0	0	0
0.6	0	0	0	0.6	0.9	0.9	0.9	0.6	0	0	0
0.7	0	0	0	0.6	0.6	0.6	0.6	0.6	0	0	0
0.8	0	0	0	0	0	0	0	0	0	0	0
0.9	0	0	0	0	0	0	0	0	0	0	0
1.0	0	0	0	0	0	0	0	0	0	0	0

Figure 4.6: Translational Model Program - Cost vs. Practicality Matrix

Finally, the Sustainability graph is displayed in Figure 4.7.

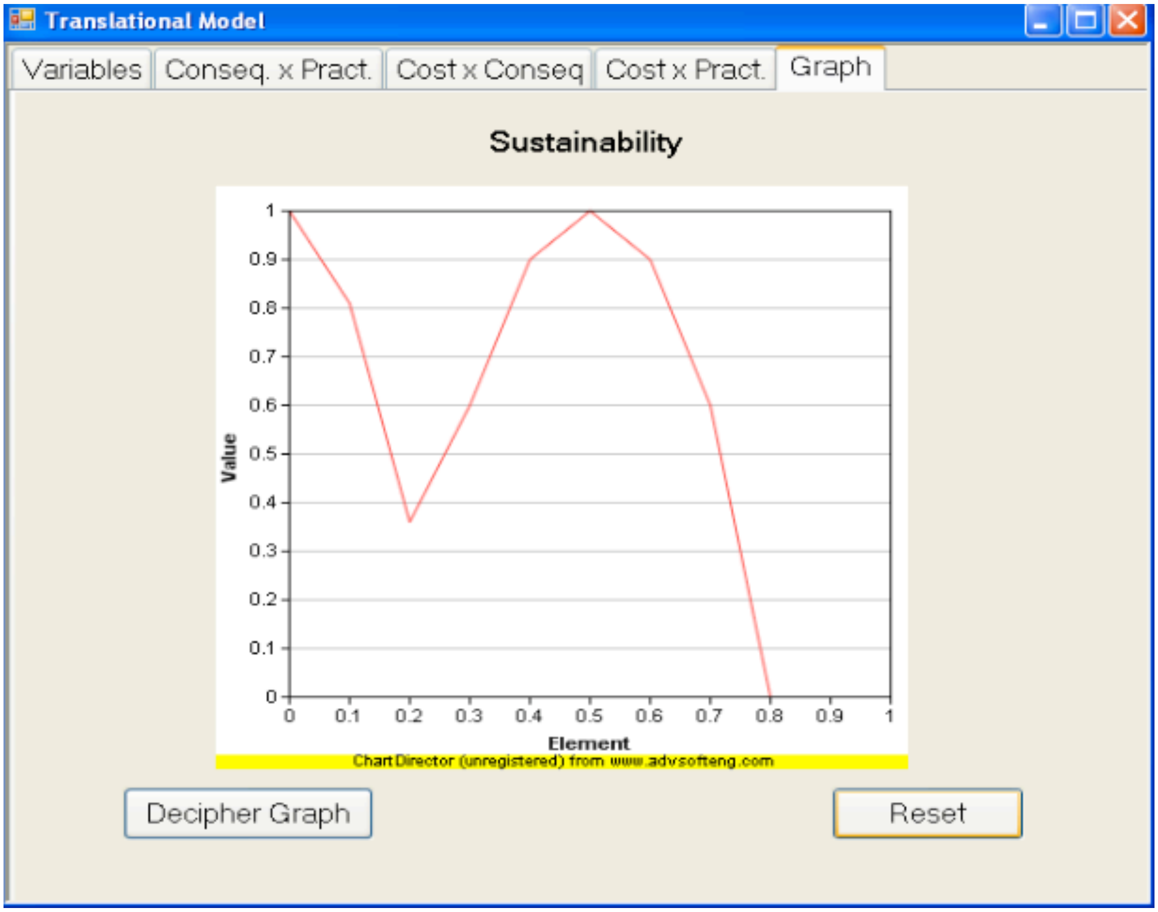


Figure 4.7: Translational Model Program- Sustainability Membership Values Graph

If the user is confused about how to read the graph, a 'Decipher Graph' button can be pressed, giving the user guidance on how to read the trends in the graph, Figure 4.8. In this case, the graph would be deciphered as 'Moderate to Very Unsustainable'.

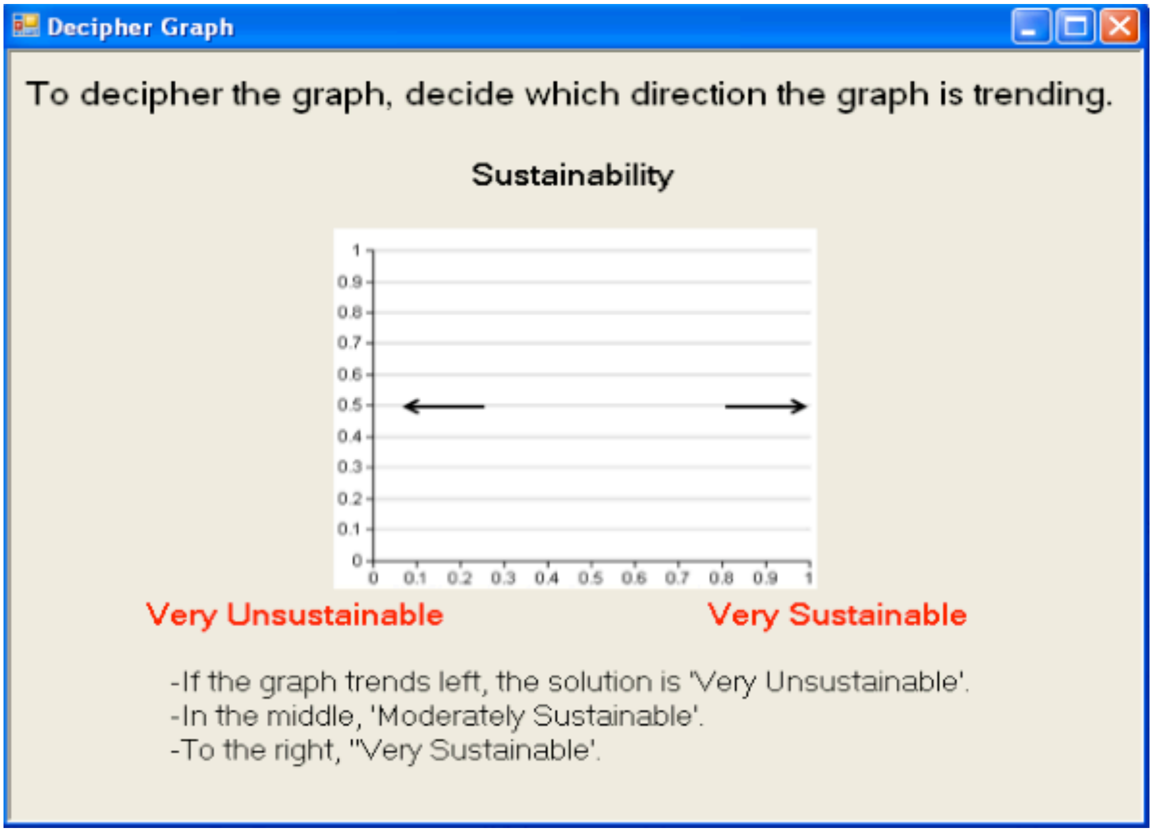


Figure 4.8: Translational Model Program - Decipher Graph Help Screen

Additional examples of the Translational Model can be found in Appendix A.

CHAPTER 5 : MAMDANI MODEL

5.1 Introduction

This chapter discusses the use of fuzzy set Mamdani model to convert linguistic expressions into numerical sets. The Mamdani model of the fuzzy set concept is applied in this chapter by taking two inputs, Practicality and Cost of local materials, and determining the overall sustainability of a concrete pile construction process.

5.2 Mamdani Approach

The Mamdani Model is taken from Al-Humaidi [1].

The Mamdani approach uses a fuzzy controller, which is structured using four components; these four units consist of a fuzzification unit, a rule base unit, an inference engine, and a defuzzification unit. The structure of a fuzzy controller structure is shown in Figure 5.1.

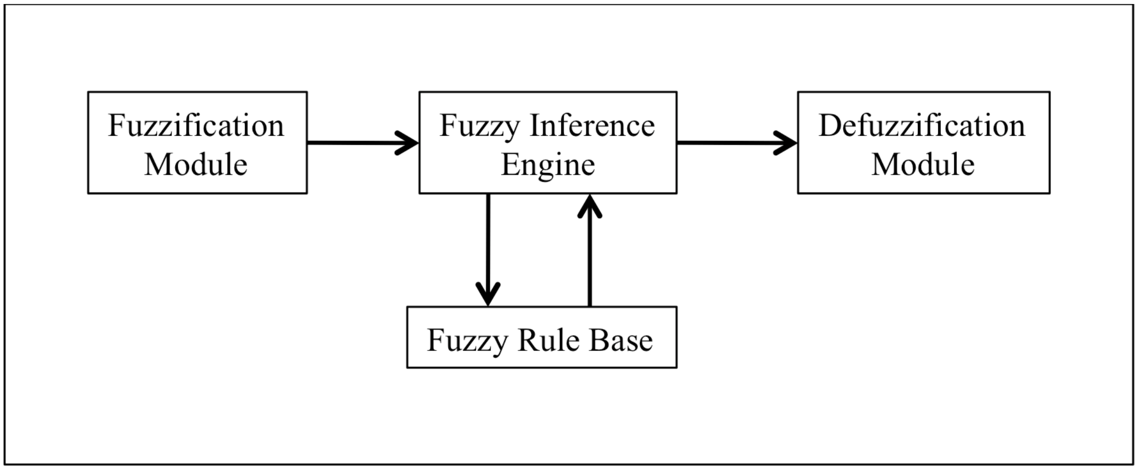


Figure 5.1: Mamdani Model - Fuzzy Controller

The fuzzy controller works in four steps, seen in Figure 5.2. First, the user (engineer, construction manager, or expert) will assess practicality and cost of using local materials in the piles. This assessment is based on numerical quantities ranging from -100% to 100%. -100% correlates to a very impractical or impossible situation, or high cost. 100% correlates to a very ideal practical situation, or very low cost. Next, these values are converted into their respective fuzzy sets, called fuzzification. These fuzzified values are then used by the fuzzy inference engine to evaluate the control rules stored in the fuzzy rule base. The result of this is a fuzzy set, or several fuzzy sets, defining the sustainability of the piles. The final step, defuzzification, is where the fuzzy sets are converted into a single value representing the sustainability of the piles.

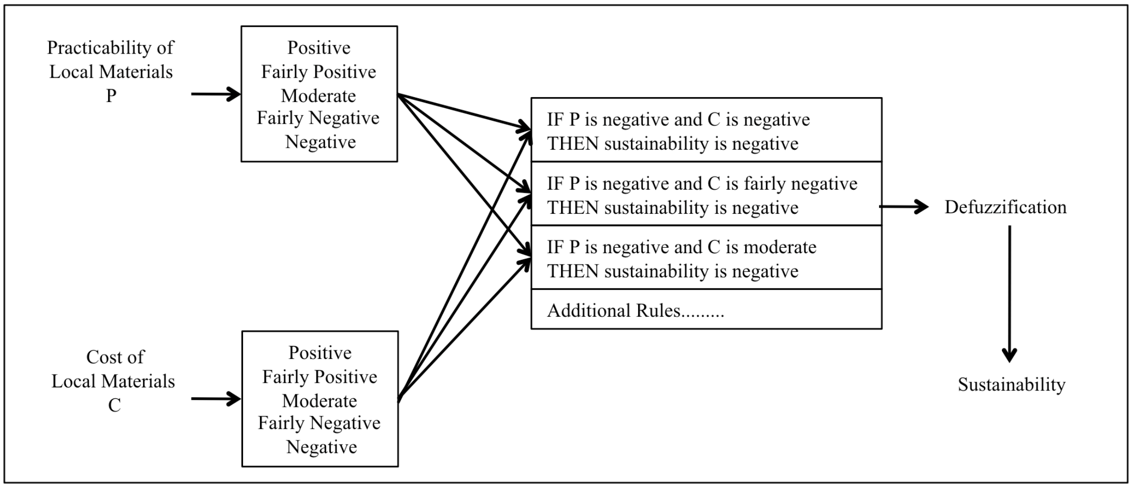


Figure 5.2: Mamdani Model - Fuzzy Controller Steps

In the first step of the fuzzy controller, the user is assessing the project. In order to do so, he/she must first have knowledge of the project and be willing to assign a numerical value to both the practicality and cost of using local materials in the concrete piles. For example, the user has selected -10% and 40%. This input value is then mapped to values from 0 to 1 using a set of input membership functions. These values can represent fuzzy concepts such as *Negative* or *Moderate* as in Table 5.1 and Figure 5.3. In the case of this particular model, these linguistic values represent practicality and cost. For example, a negative practicality is related to a project in which it would be difficult or inconvenient to implement local materials. A positive cost would be a low cost of implementing local materials.

Negative (N) = [1|-1, 0|-0.5, 0|0, 0|0.5, 0|1]
Fairly Negative (FN) = [0|-1, 1|-0.5, 0|0, 0|0.5, 0|1]
Moderate (M) = [0|-1, 0|-0.5, 1|0, 0|0.5, 0|1]
Fairly Positive (FP) = [0|-1, 0|-0.5, 0|0, 1|0.5, 0|1]
Positive (P) = [0|-1, 0|-0.5, 0|0, 0|0.5, 1|1]

Table 5.1: Mamdani Model - Membership Values

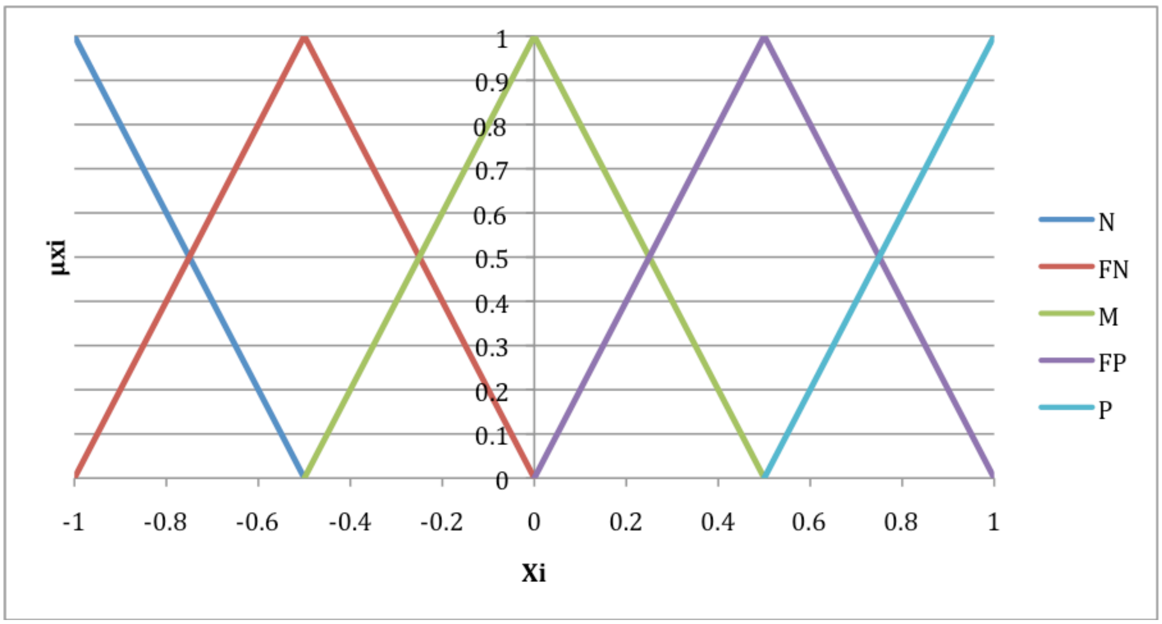


Figure 5.3: Mamdani Model - Membership Values

These input are then mapped into fuzzy numbers by marking the intersection of input membership functions, as in Figure 5.4 and Figure 5.5.

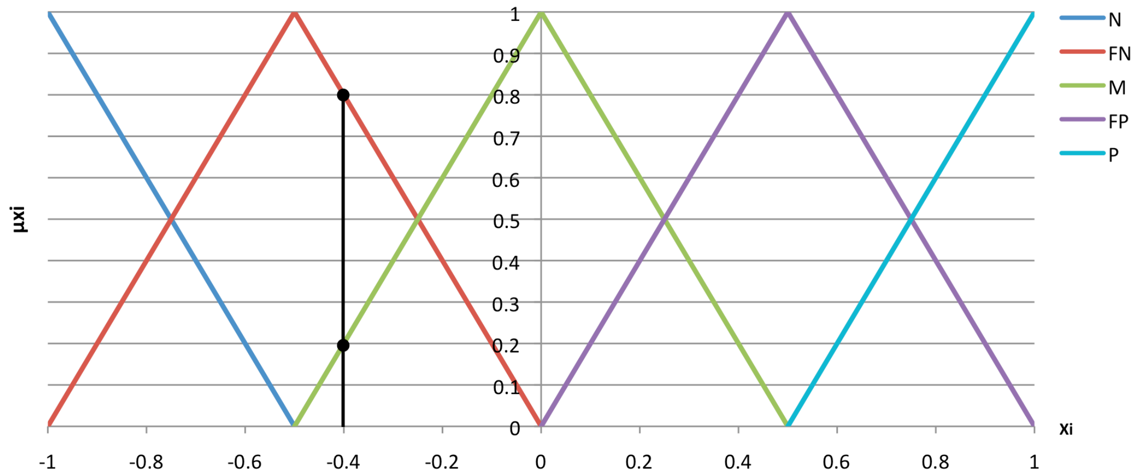


Figure 5.4: Mamdani Model – First Intersection of Input Membership Functions

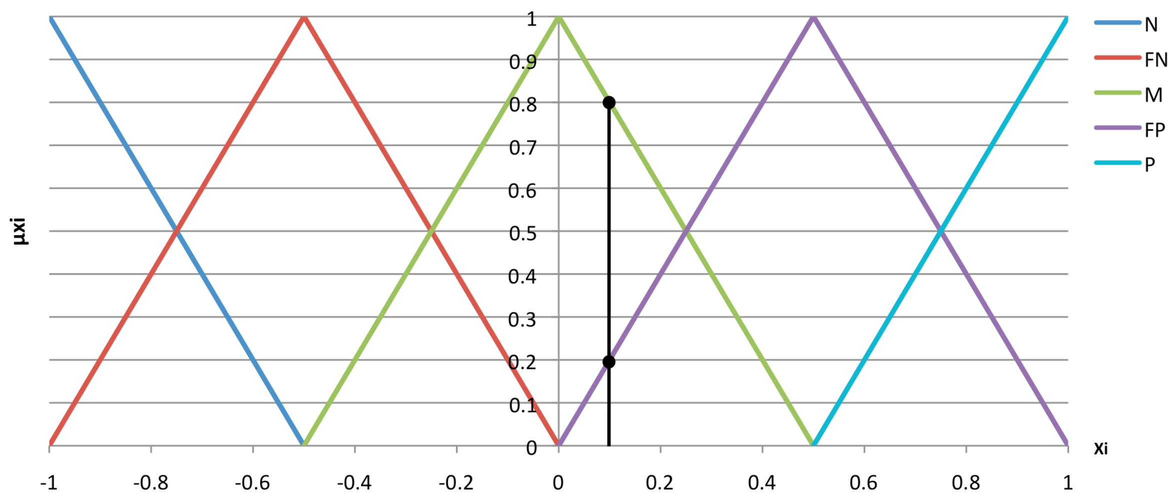


Figure 5.5: Mamdani Model – Second Intersection of Input Membership Functions

Fuzzy rules must be formed in order to determine the sustainability of certain input combinations. These rules are written in the following form:

If (input 1 is membership function 1) and (input 2 is membership function 2) Then (output is output membership function).

The rules for this model are found in Table 5.2.

			Cost		
Sustainability	**Negative (High)**	**Fairly Negative**	**Moderate**	**Fairly Positive**	**Positive (Low)**
Practicality					
Negative	Negative	Negative	Negative	Negative	Negative
Fairly Negative	Negative	Fairly Negative	Fairly Negative	Fairly Negative	Fairly Negative
Moderate	Negative	Fairly Negative	Moderate	Moderate	Moderate
Fairly Positive	Negative	Fairly Negative	Moderate	Fairly Positive	Fairly Positive
Positive	Negative	Fairly Negative	Moderate	Fairly Positive	Positive

Table 5.2: Mamdani Model Rules

For the example P = -10%, C = 40%, the rules are:

Rule 1: If Practicality is *Moderate* and Cost is *Moderate*, then the sustainability is *Moderate.*

Rule 2: If Practicality is *Moderate* and Cost is *Fairly Negative*, then the sustainability is *Fairly Negative.*

Rule 3: If Practicality is *Fairly Positive* and Cost is *Moderate*, then the sustainability is *Moderate.*

Rule 4: If Practicality is *Fairly Positive* and Cost is *Fairly Negative*, then the sustainability is *Fairly Negative.*

The way to define the result of the rules in this model is by using the “max-min” inference method. This method uses two operations; the “AND” operation and the “OR” operation combined. The fuzzy “AND” and “OR” operations are written as follows:

$$u_{A \cap B} = \min(u_A(x), u_B(x)) \tag{5.1}$$

$$u_{C \cup D} = \max(u_C(x), u_D(x)) \tag{5.2}$$

The combination of the two operations is:

$$z = [\, (A_1 \cap B_1) \cup (A_2 \cap B_2) \cup (A_1 \cap B_1) \cup (A_2 \cap B_2) \,] \tag{5.3}$$

To accomplish this method graphically, first see the intersections in Figure 5.4 and Figure 5.5. There are two intersection points for each variable. Thus, there will be four different combinations (corresponding to the four rules). Using Figure 5.6, the graphs on the left are compared. The minimum height is taken (0.2 and 0.8) and the minimum of (Mod, Mod). A new graph is made on the right.

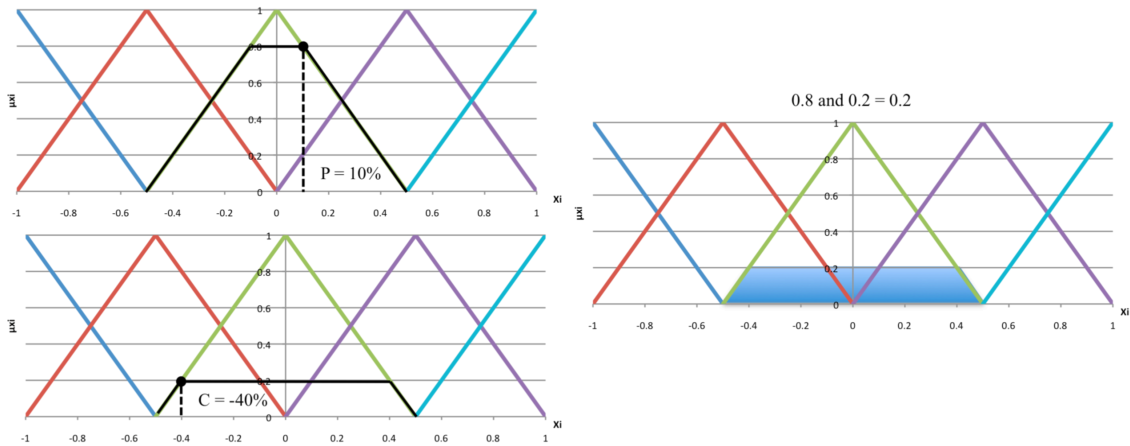


Figure 5.6: Mamdani Model - Rule 1 (0.8, 0.2) and (M, M)

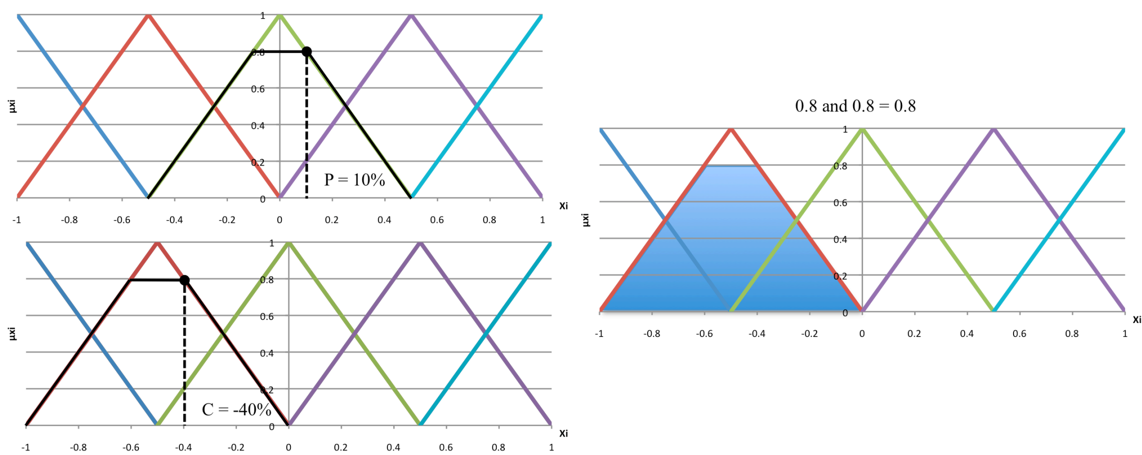


Figure 5.7: Mamdani Model - Rule 2 (0.8, 0.8) and (M, N)

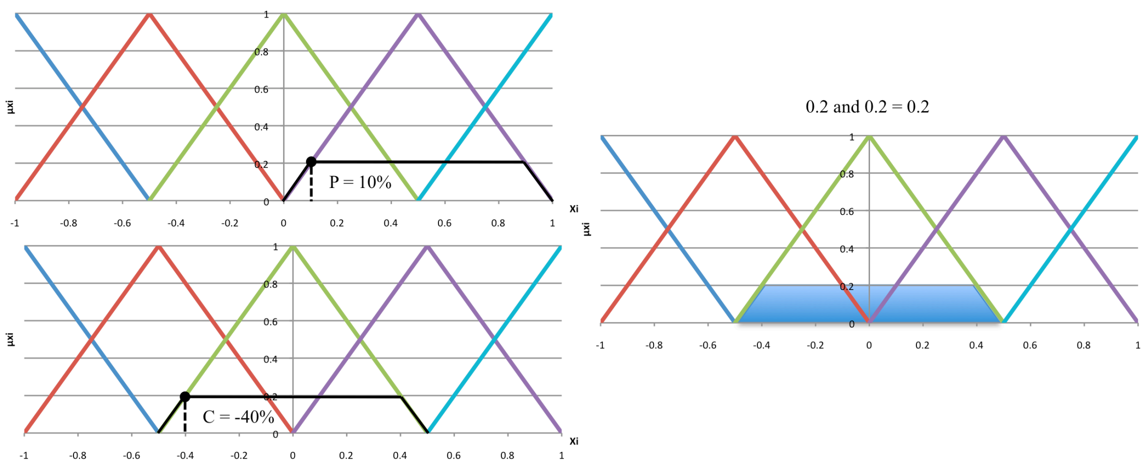


Figure 5.8: Mamdani Model - Rule 3 (0.2, 0.2) and (FP, N)

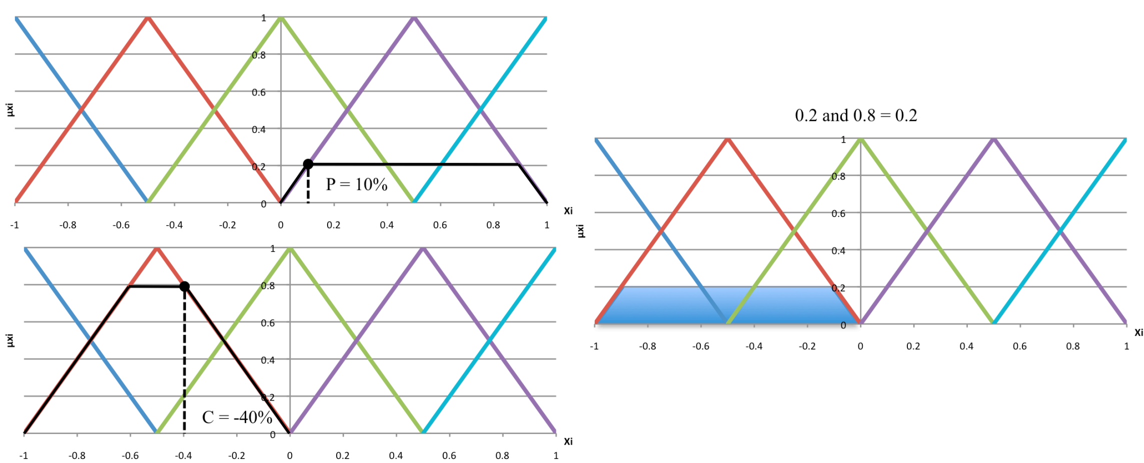


Figure 5.9: Mamdani Model - Rule 4 (0.2, 0.8) and (FP, FN)

Next, the four graphs will be compared, taking the maximum values across the x-axis, as seen in Figure 5.10.

Lastly, the result needs to be 'defuzzified', using the weighted average method. This method uses the following formula [9]:

$$x^* = \sum \mu_C(\varkappa).x \,/\, \sum \mu_C(\varkappa) \tag{5.4}$$

where x^* is the defuzzified value; $\varkappa$ is the centroid of the four contributing membership functions. In this example, $x^* = -0.37$, signified by the red arrow.

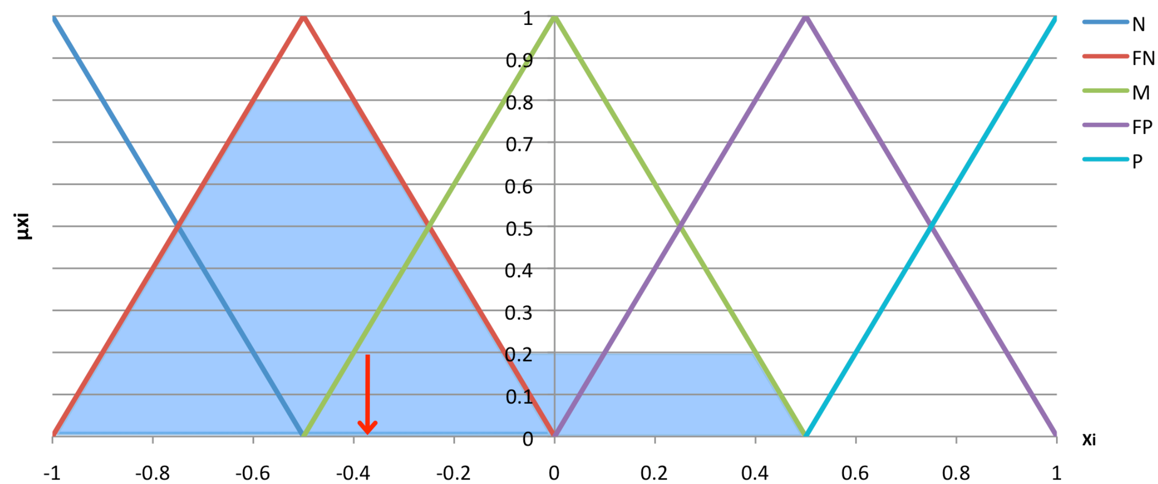


Figure 5.10: Mamdani Model - Final Graph with Weighted Average Centroid Value

5.3 Software Program

A program was written in order to take a user-defined condition to give a graphical answer. The user will enter the value of *Practicality* and *Cost*, as in Figure 5.11.

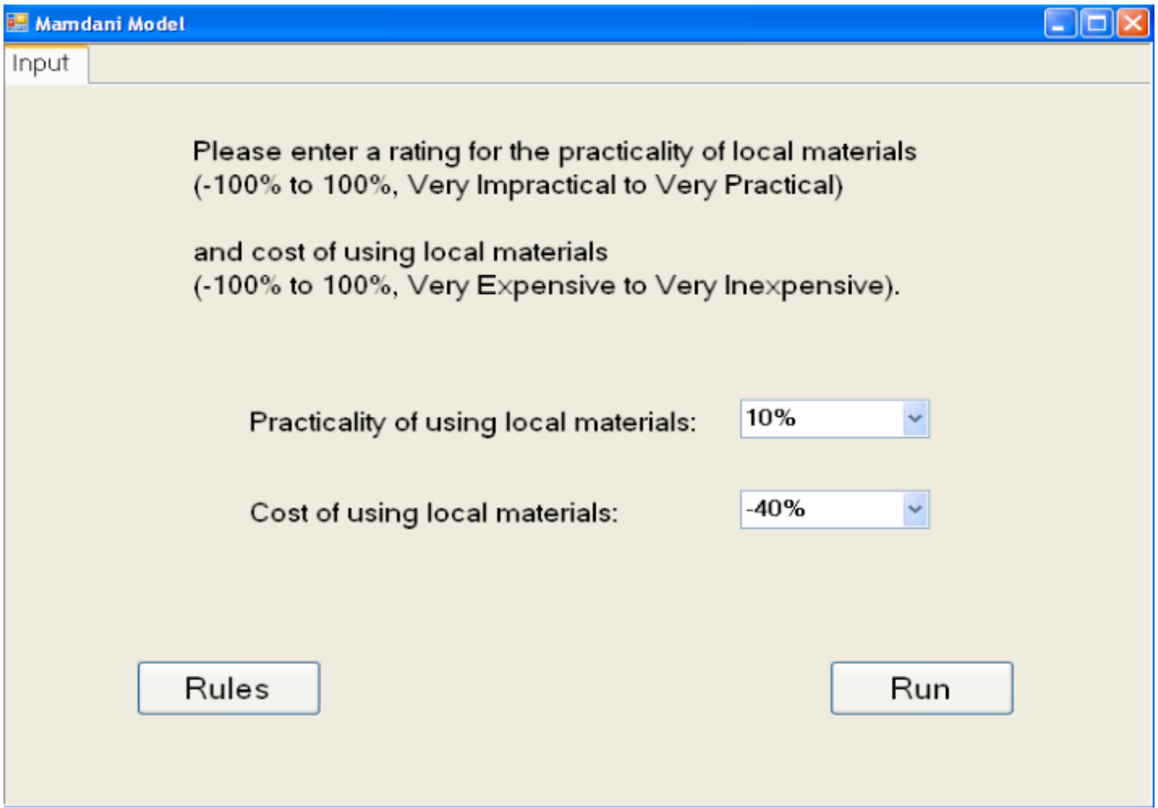


Figure 5.11: Mamdani Model Program - User Input

If the knowledge engineer would like to see the rules associated with the model, they can press 'Rules' and get Figure 5.12.

Rules

		Cost				
	Sustainability	**Negative (High)**	**Fairly Negative**	**Moderate**	**Fairly Positive**	**Positive (Low)**
Practicality	**Negative**	Negative	Negative	Negative	Negative	Negative
	Fairly Negative	Negative	Fairly Negative	Fairly Negative	Fairly Negative	Fairly Negative
	Moderate	Negative	Fairly Negative	Moderate	Moderate	Moderate
	Fairly Positive	Negative	Fairly Negative	Moderate	Fairly Positive	Fairly Positive
	Positive	Negative	Fairly Negative	Moderate	Fairly Positive	Positive

Figure 5.12: Mamdani Model Program Rules

In the 'output' tab in Figure 5.13, the four 'minimum' graphs are represented on the left, and the final graph is on the right. The weighted average centroid is shown by a blue line and the value is represented by 'I'. Additionally, a linguistic value is attached to this centroid, giving a degree of sustainability of *Poor*.

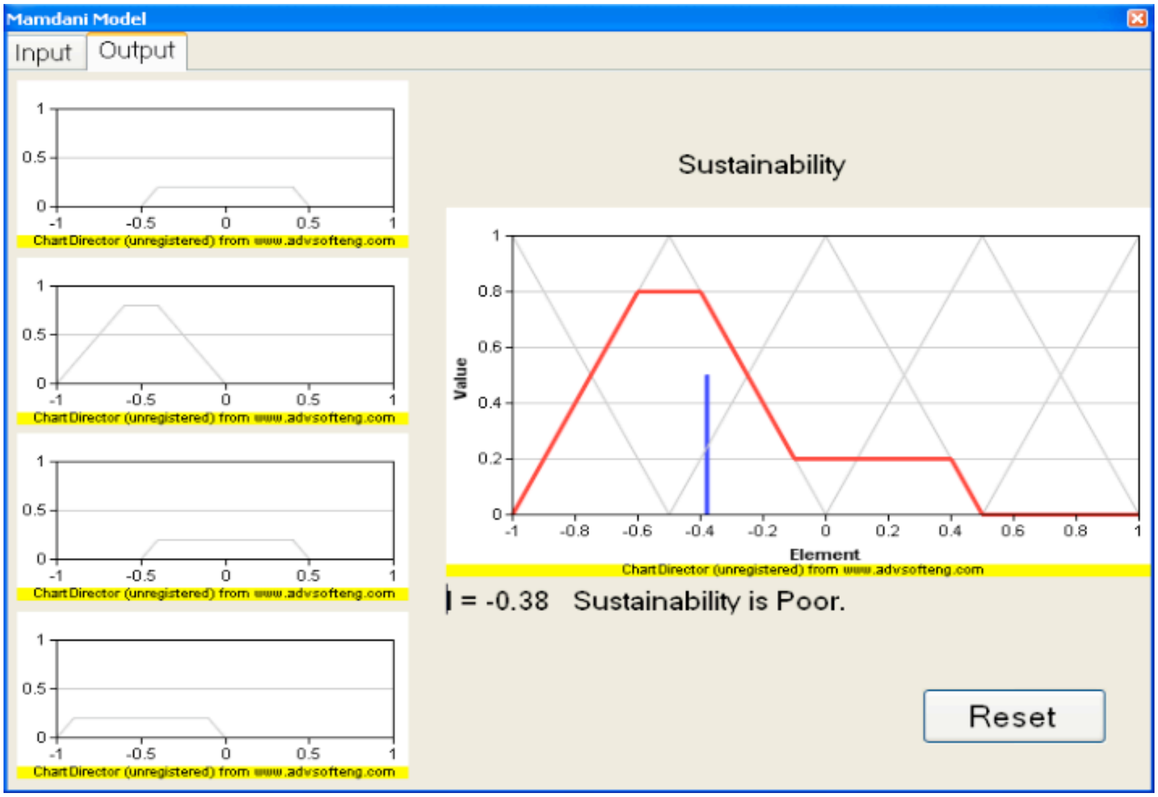


Figure 5.13: Mamdani Model Program - Sustainability Result

Additional examples of the Mamdani Model can be found in Appendix A.

CHAPTER 6 : ROTATIONAL MODEL

6.1 Introduction

This chapter will elaborate on the use of fuzzy set translation models for the assessment of concrete pile foundation sustainability. Through the use of computer programming, a model is constructed to determine pile sustainability based on use of local materials. By producing a graphical result, the user will be able to determine sustainability based on the rules entered. This model, as well as the others introduced in the research, will be compared and contrasted to find the best and most practical method.

6.2 User Assessment

The program is geared towards experts, knowledge engineers, or simply designers or construction managers familiar with the project. The program is meant to be used to evaluate different methods before construction. It is not, however, an assessment tool for existing concrete pile foundations.

The user would be familiar with the variables in Table 6.1, and able to assign values to both the amount of local materials to be in the concrete, and the overall sustainability of the piles.

Amount of Local Materials	*Sustainability*
Very Many (VM)	Very Sustainable (VS)
Many (M)	Sustainable (S)
Fairly Many (FM)	Fairly Sustainable (FS)
Fairly Few (FF)	Fairly Not Sustainable (FNS)
Few (F)	Not Sustainable (NS)
Very Few (VF)	Very Not Sustainable (VNS)

Table 6.1: Rotational Model - Pile Materials and Sustainability

6.3 Fuzzy Sets

The Rotational Model process is taken from Hadipriono [4].

The input values used for the rotational model are taken from Baldwin's truth values (Figure 6.1). These ten truth values are translated into the fuzzy set expressions as seen in Table 6.2, where 'True' is 'Sustainable', and 'False' is 'Not Sustainable' etc [9].

'True' is simply a line with a slope of 1. 'Very True' is 'True' ^{2}, and 'Fairly True' is $\sqrt{}$True. Alternatively, 'False' is a line with a slope of -1. 'Very False' and 'Fairly False' follow the same rules as their positive counterparts.

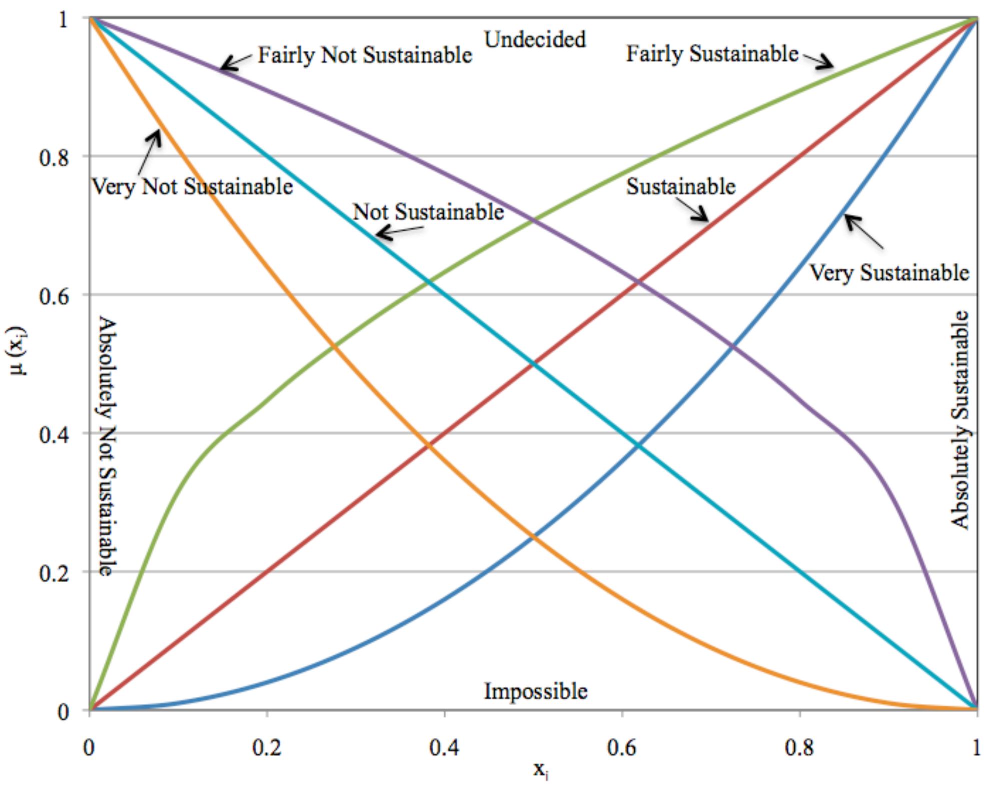


Figure 6.1: Rotational Model - Baldwin's Truth Values Graph

Truth Values	Fuzzy Set Expression					
Absolutely True	[0|0,	0.2|1,	0.4|1,	0.6|1,	0.8|1,	1|1]
Very True	[0|0,	0.04|0.2,	0.16|0.4,	0.36|0.6,	0.64|0.8,	1|1]
True	[0|0,	0.2|0.2,	0.4|0.4,	0.6|0.6,	0.8|0.8,	1|1]
Fairly True	[0|0,	0.45|0.2,	0.63|0.4,	0.77|0.6,	0.89|0.8,	1|1]
Fairly False	[1|0,	0.89|0.2,	0.77|0.4,	0.63|0.6,	0.45|0.8,	0|1]
False	[1|0,	0.8|0.2,	0.6|0.4,	0.4|0.6,	0.2|0.8,	0|1]
Very False	[1|0,	0.64|0.2,	0.36|0.4,	0.16|0.6,	0.04|0.8,	0|1]
Absolutely False	[0|0,	0.2|0,	0.4|0,	0.6|0,	0.8|0,	1|0]
Undecided	[1|0,	1|0.2,	1|0.4,	1|0.6,	1|0.8,	1|1]
Impossible	[0|0,	0|0.2,	0|0.4,	0|0.6,	0|0.8,	0|1]

Table 6.2: Rotational Model - Truth Values in Fuzzy Set Expressions

6.4 Modus Ponens Deduction

The Modus Ponens Deduction (MPD) is a fuzzy logic operation that is used to find the value of consequence in a production rule after the information about the antecedent has been given.

The modus ponens deduction states the following:

Rule: S (Amount of Local Materials) $\rightarrow$ P (Level of Sustainability)

Fact: S'

$\therefore P'$

The deduction states that, with a rule S implies P, and given S', P' can be concluded.

The deduction is broken down into three steps:

Step 1: Inverse Truth Functional Modification (ITFM)

$[S \mid S'] = T'$

Step 2: Lukasiewicz Implication Rules (LIR)

$[(S \text{ is } T') \rightarrow (P \text{ is } T)]$

Step 3: Truth Functional Modification (TFM)

$[P \text{ is } T] = P'$

6.5 Inverse Truth Functional Modification (ITFM)

Inverse Truth Functional Modification (ITFM) is a logic operation that can associate truth values with conditional proposition. ITFM reexamines the truth by modifying the proposition to capitulate a new truth value

$S \mid S'$ where S, S' $\subset \mathcal{S}$; $\forall$ x $\varepsilon\, \mathcal{S}$

$\therefore T'$ where T' $\subset \mathcal{W}$; $\forall$ ω $\varepsilon\, \mathcal{W}$

S and S' are the fuzzy sets in the Universe of Discourse $\mathcal{S}$, and T' is the fuzzy set in the Universe of Discourse $\mathcal{W}$.

The equation for T' is:

$$f_{T'}(\omega) = f_{T'}[f_S(x)] = \vee_{\forall\chi}[f_{S'}(x)] \tag{6.1}$$

$$\text{Since } f_{T'}(\omega) = f_{S'}(x), \text{ for } x = 0.5;\ f_{S'}(x) = d = 0.7 \tag{6.2}$$

Therefore, $f_{T'}(\omega) = 0.7$

Since the point 0.5 on the x-axis was chosen, $f_S(x) = 0.5$

From (1): $\omega = f_S(x)$

Therefore, $\omega = 0.5$

The corresponding x-value is $f_{T'}(\omega) = d = 0.7$

Therefore, $(f_{T'}(\omega), \omega) = (0.7, 0.5)$

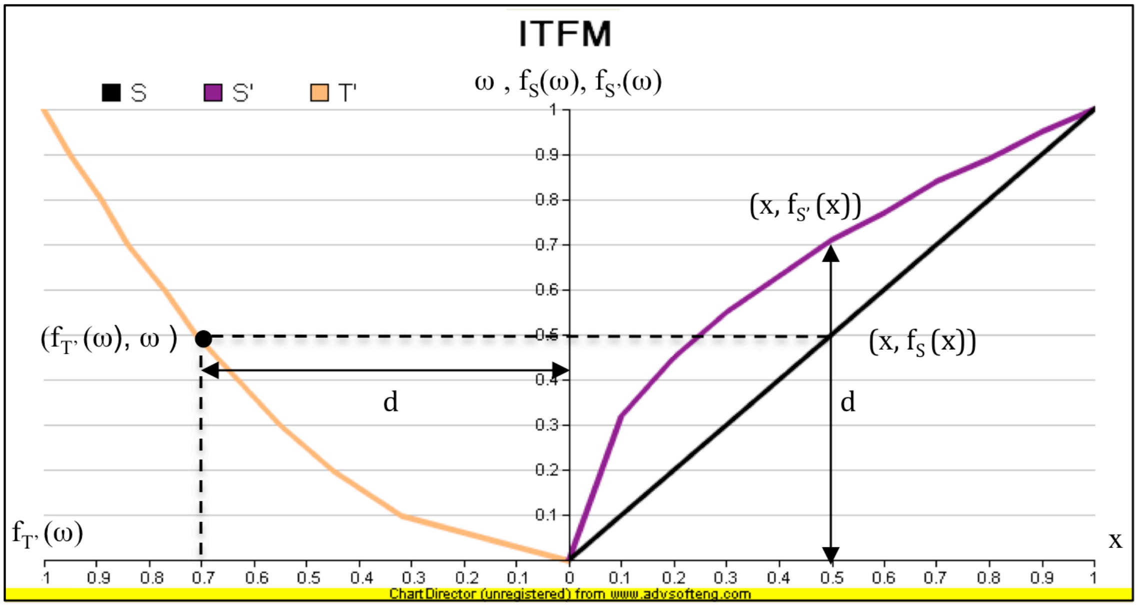


Figure 6.2: Rotational Model ITFM

6.6 Lukasiewicz Implication Relation (LIR)

The next step is Lukasiewicz Implication Relation (LIR). LIR achieves the truth value of the consequent provided that the information about the antecedent and its truth value are known.

$S \rightarrow P$ where $S, S' \subset \mathcal{S}$; $\forall\ x \varepsilon\ \mathcal{S}$; $P \subset \mathcal{P}$; $\forall\ x \varepsilon\ \mathcal{P}$

S’

(S is T’) $\rightarrow$ (P is T)

The LIR method is needed in order to make the truth relations ‘match up’. For example, the truth relation for $A \rightarrow B$ is:

$$I = \eta\ 1 \cap (1 - a + b) \qquad A \subset \mathcal{A};\ \ B \subset \mathcal{B};\ \ a\ \varepsilon\ \mathcal{A};\ \ b\ \varepsilon\ \mathcal{B} \tag{6.3}$$

	$I = A \rightarrow B$	b = 0	b = 1
a	0	1	1
	1	0	1

$$\text{If } C = [(A \rightarrow B) \cap A] \qquad (A \rightarrow B) \subset \mathcal{A} \times \mathcal{B}; \tag{6.4}$$

If S = 'true', then A = [0|0, 1|1]. A needs to be cylindrically extended in order to have the correct number of dimensions. Thus, A* is formed.

	A*	b = 0	b = 1
a	0	0	0
	1	1	1

Now, $(A \rightarrow B) \cap A^* =$ (6.5)

$$
\begin{array}{cc|cc}
 & & b & \\
I = A \rightarrow B & & 0 & 1 \\
\hline
a & 0 & 1 & 1 \\
 & 1 & 0 & 1
\end{array}
\quad \cap \quad
\begin{array}{cc|cc}
 & & b & \\
A^* & & 0 & 1 \\
\hline
a & 0 & 0 & 0 \\
 & 1 & 1 & 1
\end{array}
\quad =
$$

$$
\begin{array}{cc|cc}
 & & b & \\
C & & 0 & 1 \\
\hline
a & 0 & 0 & 0 \\
 & 1 & 0 & 1
\end{array}
$$

B = [0|0, 1|1] = 'True'

Project onto B: (0 1)

In order to find the values of T, the intersection of T' and I (ω) must be found. The equation of I (ω) is $f_I(v,\omega) = 1 \cap (1 - v + \omega)$. (6.6)

The equation of the line T is: $f_T(\omega) = \bigvee_{\forall\chi}\{[1 \cap (1 - v + \omega) \cap f_T(v)\}$. (6.7)

This equation states that for all values of v, the corresponding value for the line T is the maximum of $f_I(v,\omega) \cap f_{T'}(v)$

Graphically, looking at Figure 6.3 the points of interception of T' and I (ω) can be seen.

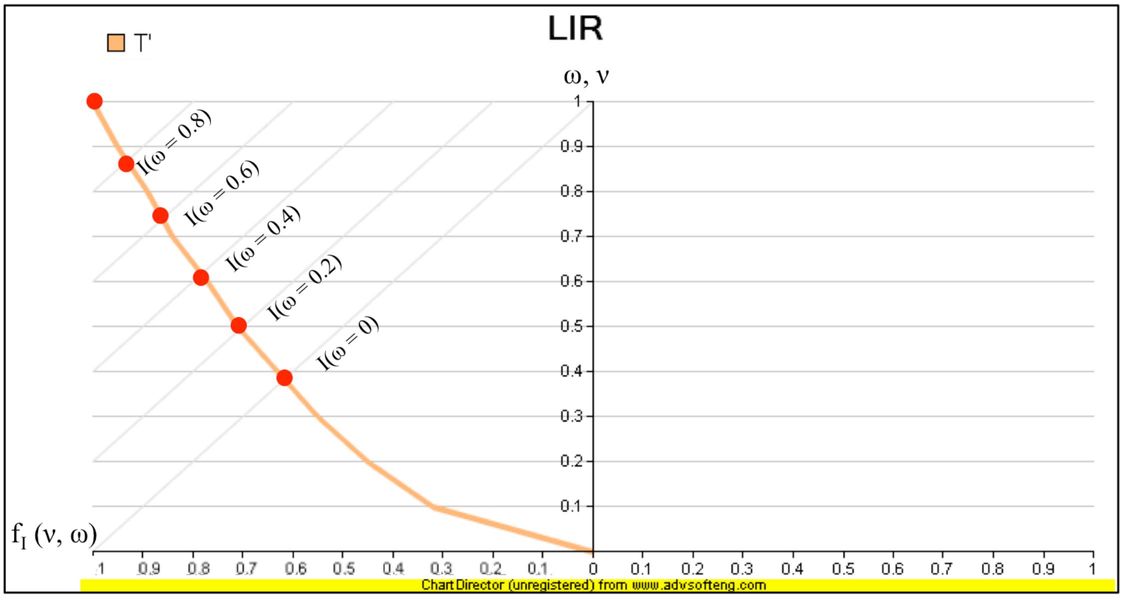


Figure 6.3: Rotational Model - LIR Intersection Points

These points are then projected downward to the corresponding ω value, as in Figure 6.4 e.g. The point of intersection with the line I (ω = 0.8) is projected down to a 'height' of ω = 0.8.

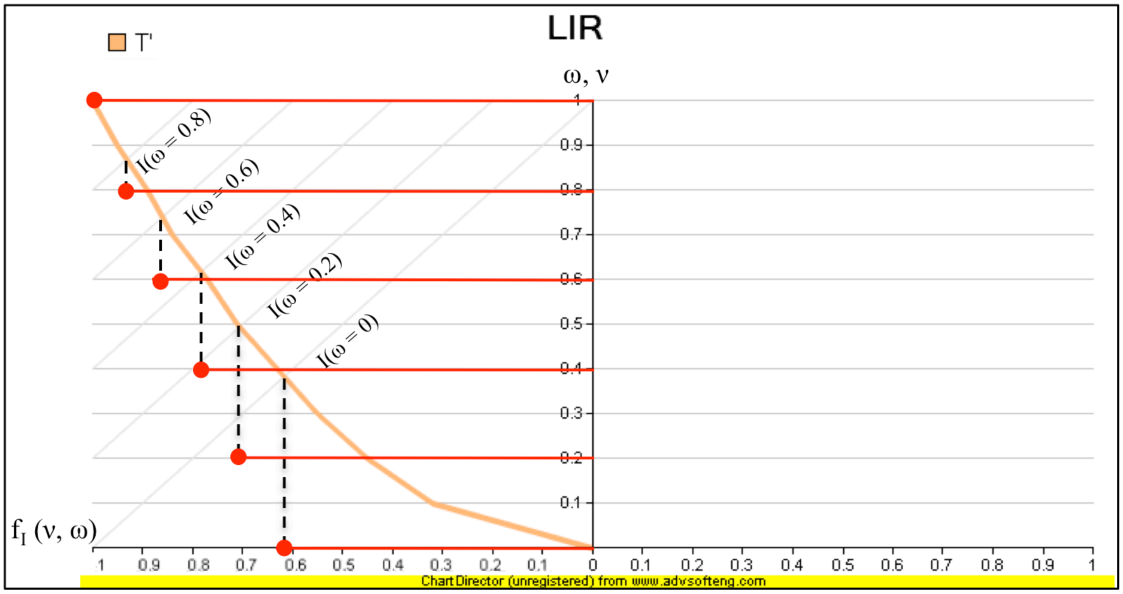


Figure 6.4: Rotational Model - LIR Projection

These points are then connected, forming the final line, T (Figure 6.5). This line has the equation $f_T(\omega) = \bigvee_{\forall\chi}\{[1 \cap (1 - v + \omega)] \cap f_T(v)\}$. (6.8)

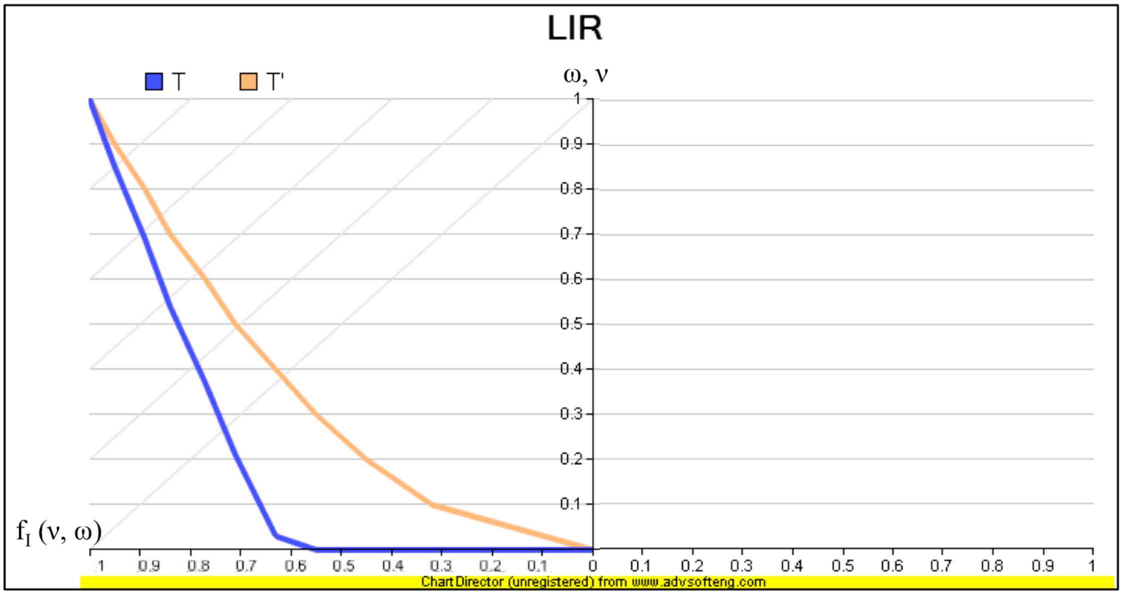


Figure 6.5: Rotational Model - Final LIR Graph

6.7 Truth Functional Modification (TFM)

Truth Functional Modification (TFM)is a logic operation that can be used to modify the membership function of a linguistic value in a certain proposition with a known truth value.

P is T where P, P' $\subset \mathcal{P}$; $\forall\, \chi \, \varepsilon \, \mathcal{P}$; T $\subset \mathcal{W}$; $\forall\, \chi \, \varepsilon \, \mathcal{W}$;

∴ P′

The equation for P' is: $f_{P'}(x) = f_T(\omega) = f_T[f_P(x)]$. (6.9)

This means that $\omega = f_P(x)$. If, for example, $x = 0.2$, then $f_P(x) = 0.2$ in Figure 6.6. Since $\omega = f_P(x)$, $\omega = 0.2$. The corresponding value of $f_T(0.2) \approx 0.71$.

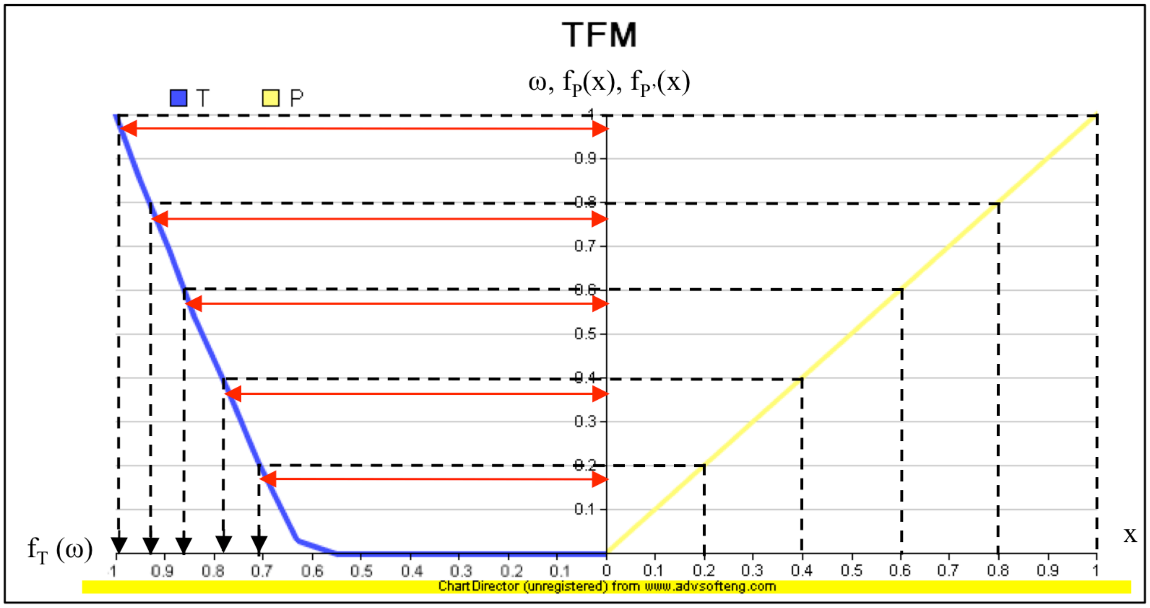


Figure 6.6: Rotational Model - TFM Projection

Next, since $f_{P'}(x) = f_T(\omega)$, the graph is essentially rotated to the right, as seen in Figure 6.7 and Figure 6.8.

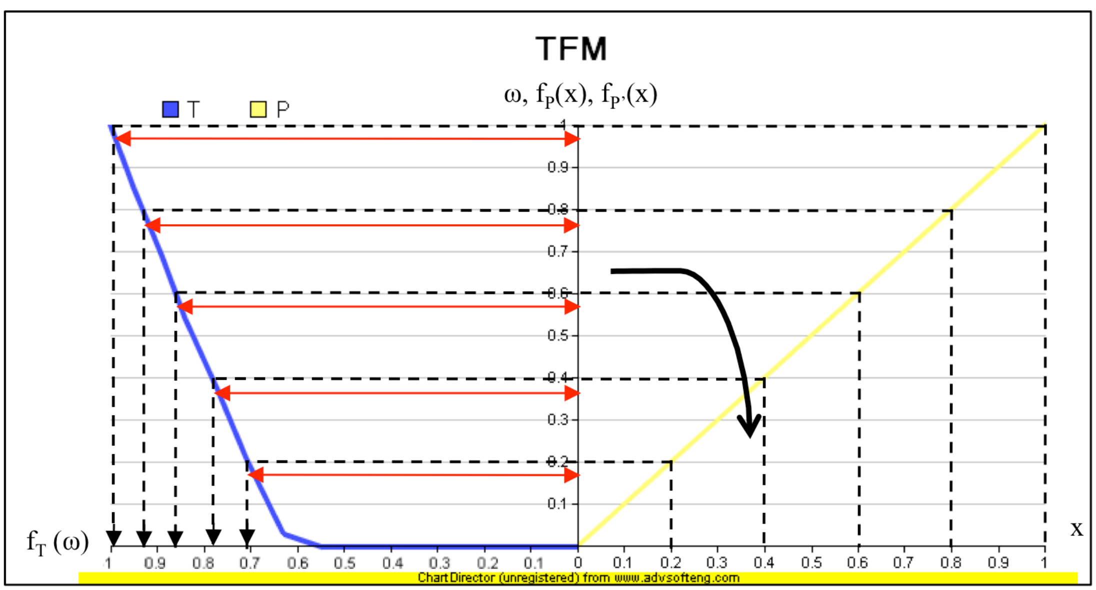


Figure 6.7: Rotational Model - Rotating TFM Graph

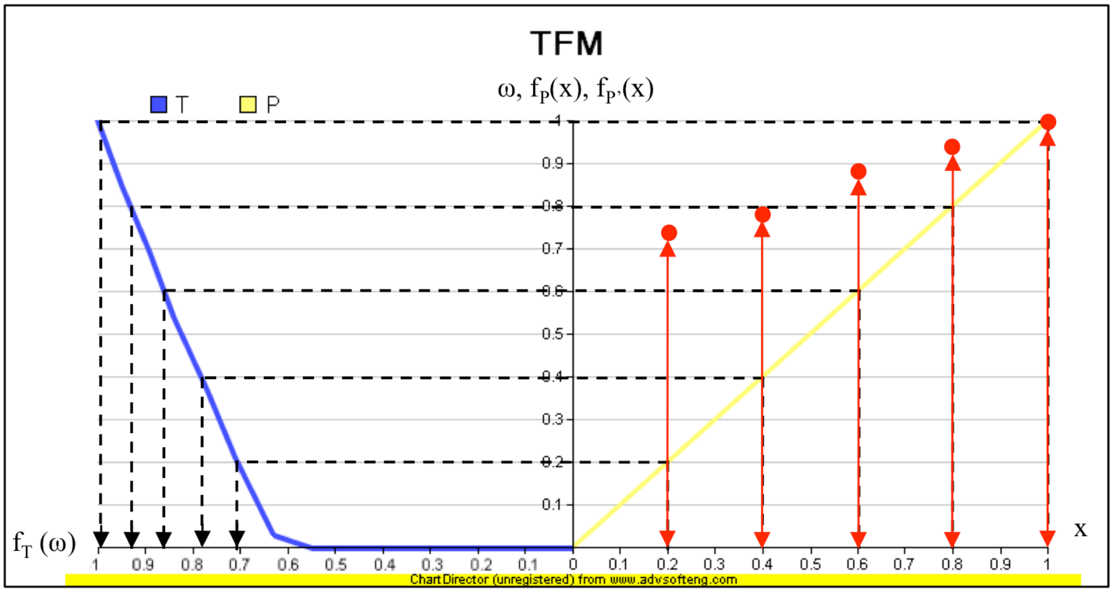


Figure 6.8: Rotational Model - Rotated TFM Graph

The points are connected to form the final graph P', is seen in Figure 6.9.

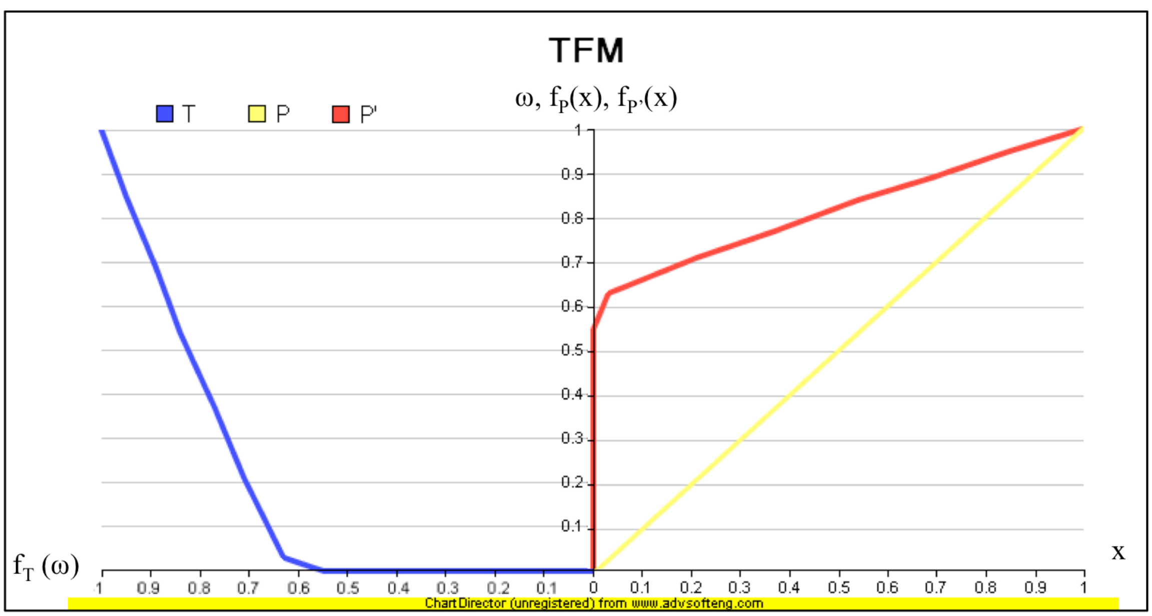


Figure 6.9: Rotational Model - Final P' Graph

6.8 Software Program

A program was written in order to take a user-defined rule and condition and give a graphical answer. The user defines the rule by inputting a value for S (amount of local materials in the concrete piles) and P (sustainability of piles). In the example (Figure 6.10), the user has defined the rule as: If the amount of local materials is '*Many*', then the piles are '*Sustainable*'. This rule will vary, depending on the 'expert' or knowledge engineer, and the conditions of the project.

Next, the condition is entered. This is simply the amount of local materials being planned for the pile project. In this example, the user has inputted the amount of local materials is '*Fairly Many'*.

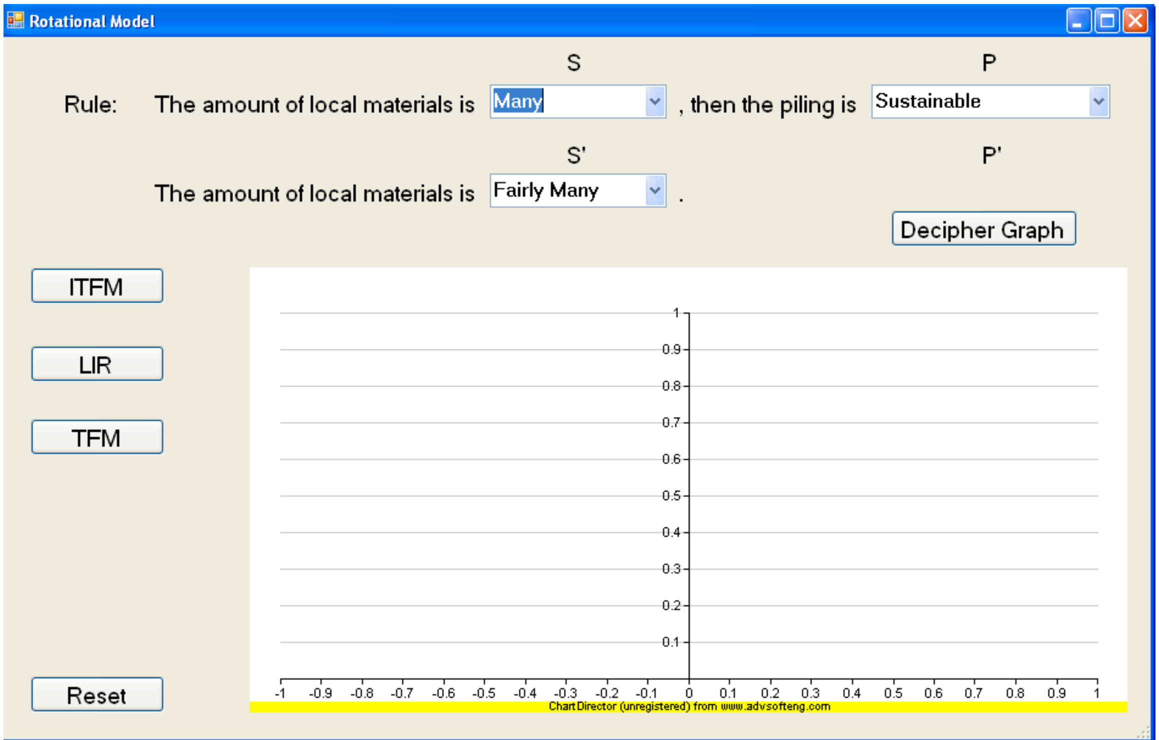


Figure 6.10: Rotational Model Program - User Input

The 'ITFM' button is pressed, displaying a graph, as in Figure 6.11. The graph displays the user-defined S and S', as well as T' on the left.

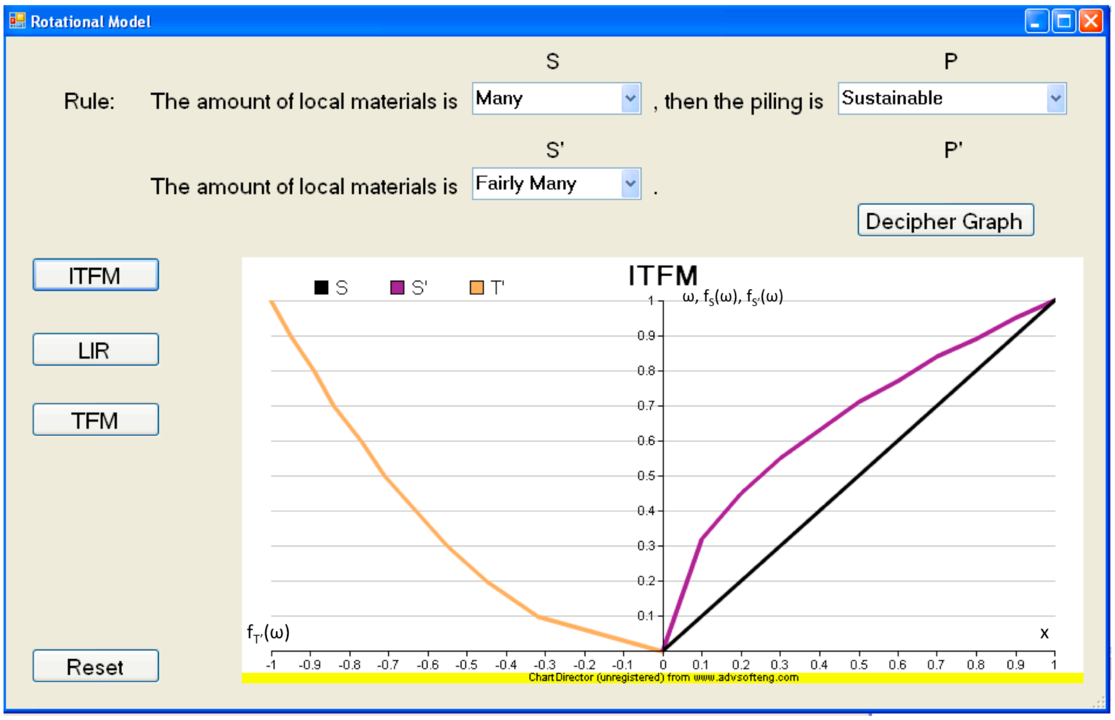


Figure 6.11: Rotational Model Program ITFM

Next, the ‘LIR’ button is pressed, displaying T’ from the previous graph, and T.

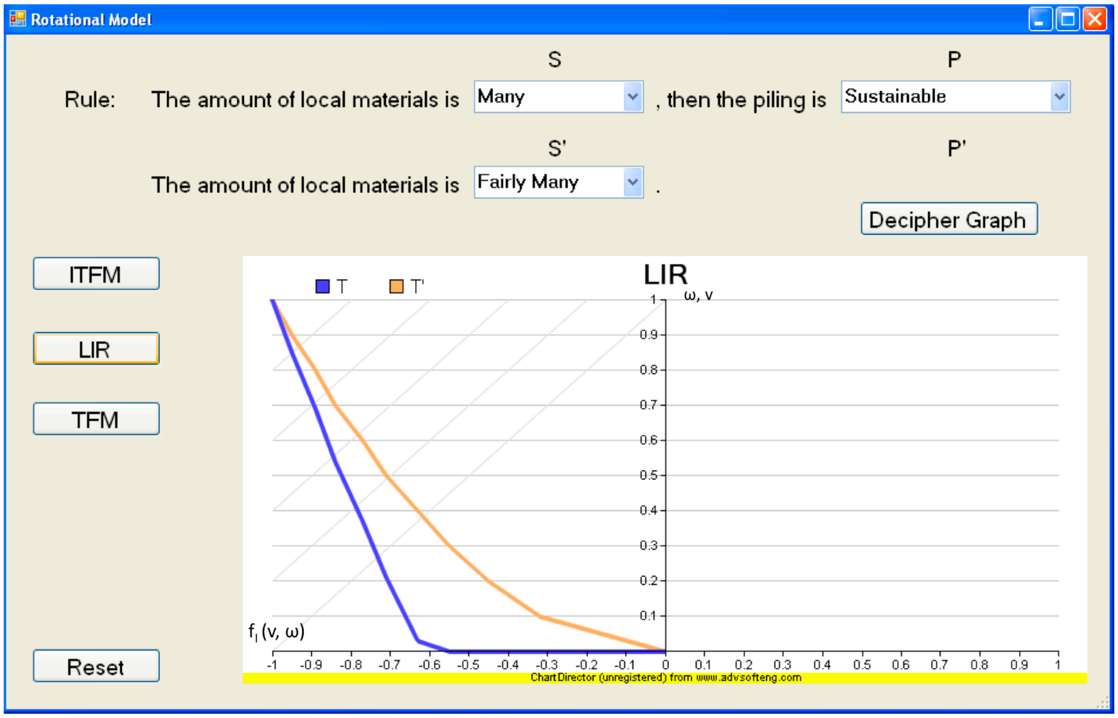


Figure 6.12: Rotational Model Program LIR

Finally, the 'TFM' button is pressed, displaying T, P, and the final result P' (Figure 6.13).

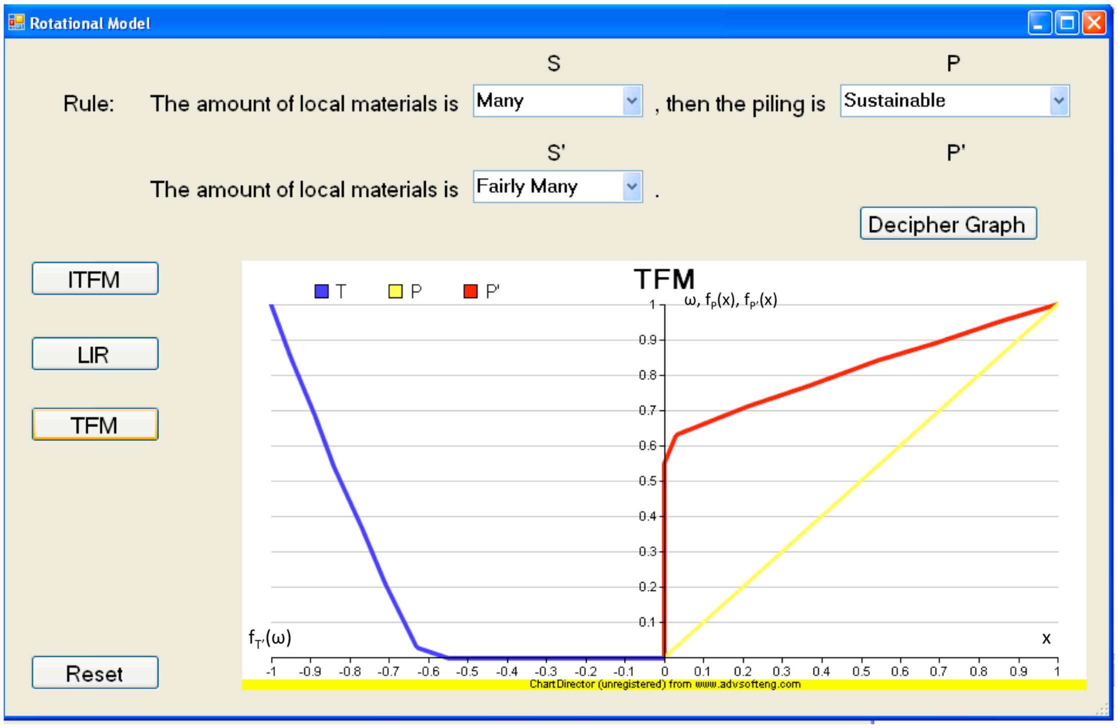


Figure 6.13: Rotational Model Program TFM

In order for a user who is not familiar with fuzzy logic to be able to read the graph, there is a ‘Decipher Graph’ button. When pressed, a separate window appears (Figure 6.14), displaying Baldwin’s Truth Values.

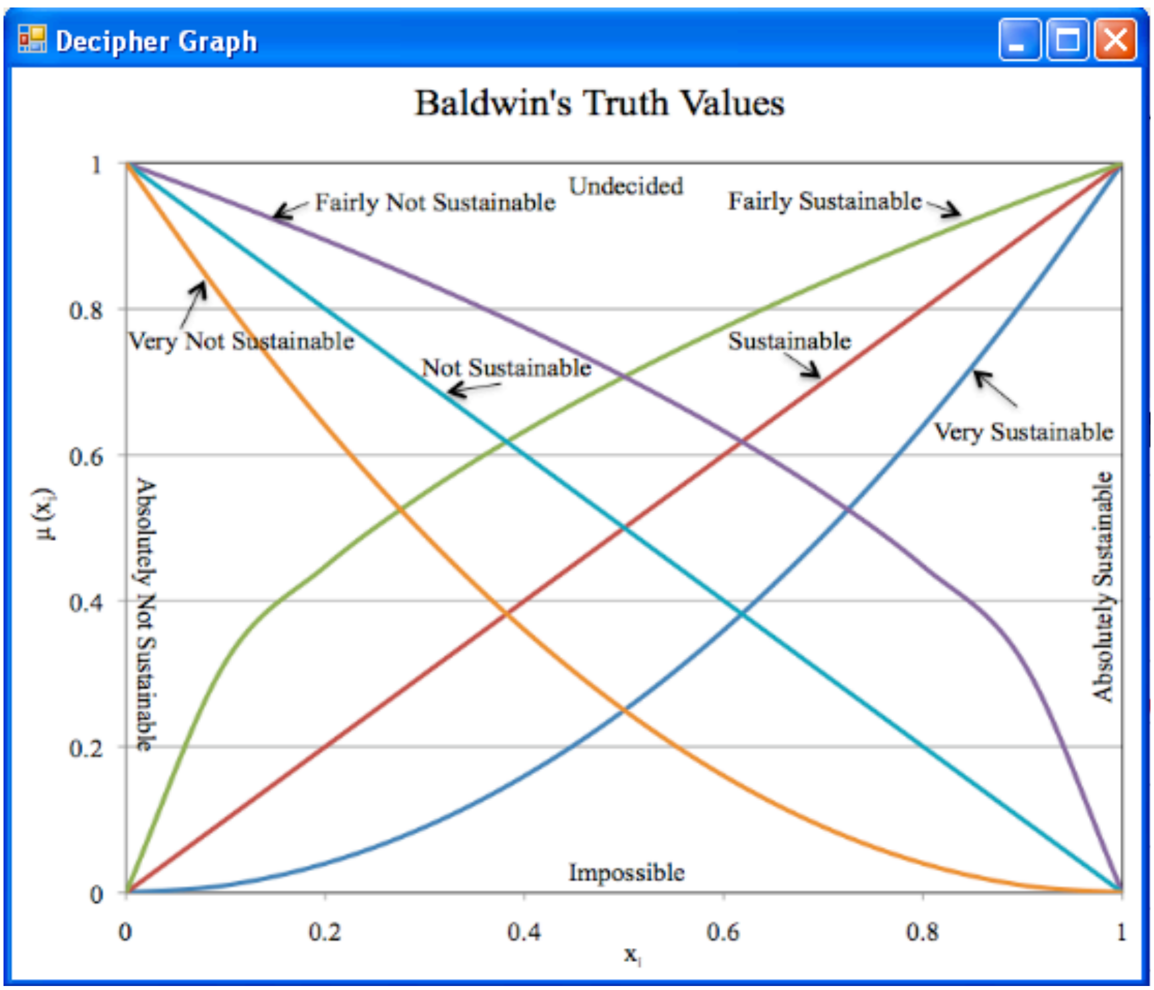


Figure 6.14: Rotational Model Program Decipher Graph

When the two graphs are compared, the user will be able to determine the final result. In the example, the P' value appears to be closest to 'Fairly Sustainable'.

Thus, the final modus ponens deduction is:

Rule: If the amount of local materials is 'Many', then the piles are 'Sustainable'.

Fact: The amount of local materials is 'Fairly Many'.

Result: The piles are 'Fairly Sustainable'.

Additional examples of the Rotational Model using the Modus Ponens Deduction can be found in Appendix A.

CHAPTER 7 : ANGULAR MODEL

7.1 Introduction

As the construction process involves many fuzzy linguistic terms, using the fuzzy set models and approaches can be very helpful in making decisions regarding material choices in concrete piles. The angular model, much like the rotational model in the previous chapter, uses the modus ponens deduction technique. The model is easy to apply, requiring relatively simple calculations, while outputting a very readable result. This chapter will describe the angular model.

7.2 Fuzzy Sets

The Angular Model process is taken from Hadipriono [5].

Unlike many other models, the linguistic truth-values in the angular model correspond to angles, as seen in Table 7.1 and Figure 7.1.

Linguistic Expression		Angular Value	
Absolutely True (AT)	Absolutely Sustainable (AS)	90º	Π/2
Very True (VT)	Very Sustainable (VS)	67.5º	3Π/8
True (TR)	Sustainable (S)	45º	Π/4
Fairly True (FT)	Fairly Sustainable (FS)	22.5º	Π/8
Undecided (U)	Undecided (U)	0º	0
Fairly False (FF)	Fairly Not Sustainable (FNS)	-22.5º	-Π/8
False (F)	Not Sustainable (NS)	-45º	-Π/4
Very False (VF)	Very Not Sustainable (VNS)	-67.5º	-3Π/8
Absolutely False (AF)	Absolutely Not Sustainable (ANS)	-90º	-Π/2

Table 7.1: Angular Model - Linguistic Expressions and Angular Values

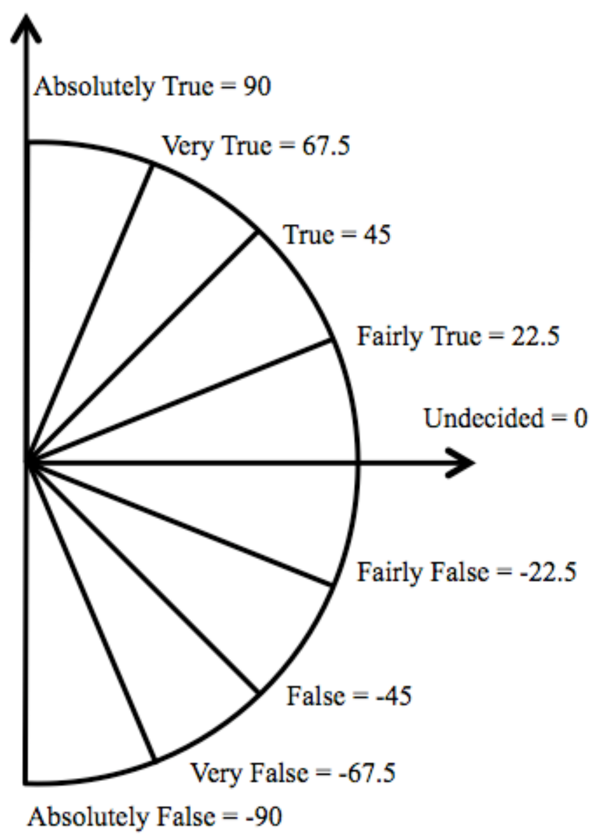


Figure 7.1: Angular Model Truth Values

Again, as in the rotational model, the modus ponens deduction states the following:

Rule: S (Amount of Local Materials) $\rightarrow$ P (Level of Sustainability)

Fact: S'

$\therefore P'$

This relationship can be further broken down:

Antecedent 1: (s is S) $\rightarrow$ (p is P) S, S' $\subset \mathcal{U}$

Antecedent 2: (s is S') P, P' $\subset \mathcal{V}$

Consequent : Q(p is P) is τ_P and (p is P') $\tau_P \subset \mathcal{T}$ (7.1)

In the proceeding propositions, s and p are the names of objects; S and S' are fuzzy sets in the universe of discourse $\mathcal{U}$ ($\subset$ denotes 'a subset of'); P and P' are fuzzy sets in the universe of discourse $\mathcal{V}$; τ_B is a new truth fuzzy set value in the truth space $\mathcal{T}$.

The angular model relies on calculations to proceed to the result. Using the Truth Functional Modification (TFM) and Inverse Truth Functional Modification (ITFM) logic operations, modus ponens deduction can be carried out.

7.3 Truth Functional Modification (TFM)

$$\Omega: (s \text{ is } S) \text{ is } \tau_s; \qquad S \subset \mathcal{U}; \;\; \tau_s \subset \mathcal{T} \tag{7.2}$$

where truth restriction τ_s is the value of $\mathcal{T}$.

$$\Omega: (s \text{ is } S'); \qquad S' \subset \mathcal{U}; \tag{7.3}$$

The membership function of S':

$$\Phi_{S'}(z) = \Phi_{\tau s} [\Phi_s(z)] \tag{7.4}$$

where $\Phi_{\tau s}$ (t) is the membership function of the truth restriction τ_S.

Now, assume the angles of S and τ_S are α and β, as seen in Figure 7.2.

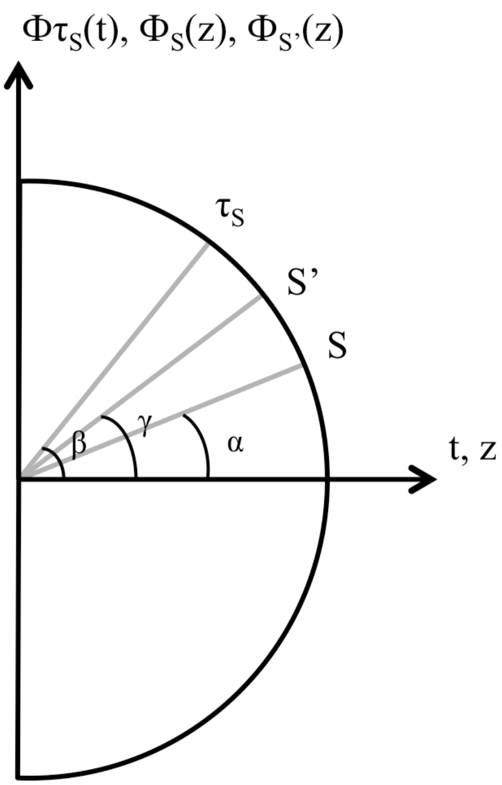


Figure 7.2: Angular Model - TFM Angles

The membership functions of S and τ_S are:

$\Phi_s(z) = z \tan \alpha$ and $\Phi_{\tau s}(t) = t \tan \beta$ (7.5)

From (4) and (5):

$\Phi_{S'}(z) = \Phi_{\tau s}[z \tan \alpha] = z \tan \alpha \tan \beta$ (7.6)

$\Phi_{S'}(z) = z \tan \gamma$ (7.7)

where $\tan \gamma = \tan \alpha \tan \beta$ (7.8)

7.4 Inverse Truth Functional Modification (ITFM)

$Q(s \text{ is } S \,/\, s \text{ is } S') = \tau_S; \qquad \tau_S \subset T; \quad S, S' \subset U$ (7.9)

where τ_S is the new truth restriction of the truth-value for fuzzy set A.

The membership value for τ_S is:

$\Phi_{\tau S}(t) = \Phi_{\tau S}[\Phi_s(z)] = \vee_z [\Phi_{s'}(z)]$ (7.10)

where $\vee_z$ denotes the value where z is maximized.

Proposition Ω from (2) now becomes Ω': (s is S) is τ_S. Therefore, the proposition is now:

Ω: (s is S) / (s is S'); $\qquad S, S' \subset U$;

Ω': (*s* is *S*) is τ_S; $\qquad \tau_S \subset T$; (7.11)

Now assume that the membership functions of S and S' are α and α' as seen in Figure 7.3.

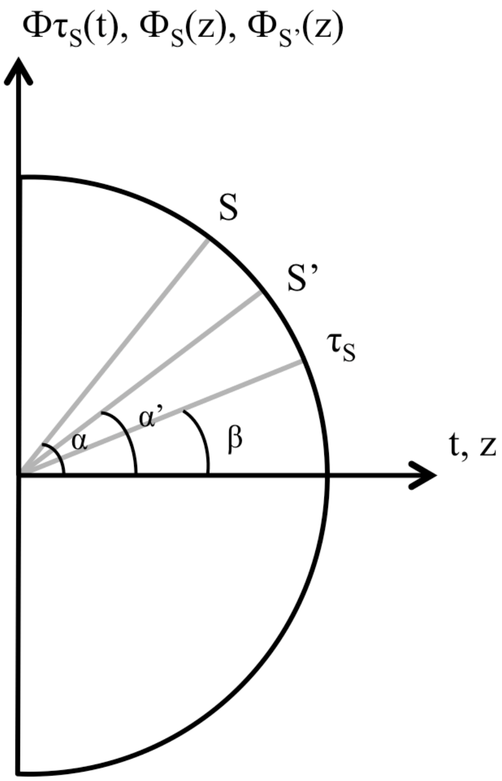


Figure 7.3: Angular Model - ITFM Angles

The membership functions of S (5) and S' are:

$\Phi_S(z) = z \tan \alpha$ and $\Phi_{S'}(z) = z \tan \alpha'$ (7.12)

From (12) and (10):

$\Phi_{\tau S}(t) = \Phi_{\tau S}[\Phi_S(z)] = \Phi_{\tau S}[z \tan \alpha] = z \tan \alpha \tan \beta$

and $\Phi_{\tau S}(t) = \vee_z [\Phi_{S'}(z)] = \vee_x [z \tan \alpha']$

so that z tan α tan β = z tan α'. For $z \neq 0$:

$$\tan\beta = \tan\alpha' / \tan\alpha \tag{7.13}$$

and $\Phi_{\tau S}(t) = t \tan\beta = t \tan\alpha' / \tan\alpha$ (7.14)

7.5 Modus Ponens Deduction

Equation (1), through ITFM becomes:

$$\Omega\text{: (s is S) is } \tau_s \supset \text{(p is P)} \tag{7.15}$$

The membership function of τ_P is:

$$\Phi_{\tau P}(y) = \vee_{\chi} [\, \Phi_{\tau S}(x) \wedge \Phi_1 (x,y) \,] \tag{7.16}$$

where x and y are elements of the truth spaces $\mathcal{T}$ and $\mathcal{T}'$ of the propositions (s is S) and (p is P), respectively; Φ_1 (x,y) is the truth implication relation function of the proposition (s is S) $\supset$ (p is P), and the $\wedge$ symbol denotes the conjunction (minimum) of $\Phi_{\tau S}(x)$ and $\Phi_1(x,y)$.

The truth implication relation function $\Phi_1(x,y)$ must be defined for the AFSM. According to Lukasiewicz law, the implication relationship function of proposition A and B according to Giles is:

$$\langle A \supset B \rangle = \sup \{0, \langle B \rangle - \langle A \rangle\}$$

where $\langle A \rangle$, $\langle B \rangle$, and $\langle A \supset B \rangle$ are the membership functions of propositions A, B, and $A \supset B$.

By Lukasiewicz theory:

$\Phi_1(x,y) = y\text{-}x \quad (x \geq 0, y \geq 0)$ (7.17)

Using Blockley's method of shorthand (e.g. using S instead of (s is S)), equation (1) can be rewritten as:

$$\begin{array}{ll} [S \supset P] \text{ is } \tau_1: & S, S' \subset \mathcal{U} \\ S' \text{ is } \tau_2; & P, P' \subset \mathcal{V} \\ \hline Q(P) \text{ is } \tau_P \text{ and } P'; & \tau_P \subset \mathcal{T} \end{array} \tag{7.18}$$

where τ_1 and τ_2 are truth restriction of implication relation $\Phi_1(x,y)$ and of proposition (s is S'), respectively.

Using fuzzy sets to represent membership functions:

$S = \Phi_S(z) = z \tan S$; $S' = \Phi_{S'}(z) = z \tan S'$; $P = \Phi_P(z) = z \tan P$; $P' = \Phi_{P'}(z) = z \tan P'$

Using TFM and ITFM, proposition S and S' can be combined:

$Q(S/S') = \tau_S = \text{ITFM} [\ S/\text{TFM}(S',\tau_2)]$

$\tau_S = t \tan S' \tan \tau_2 / \tan A$ (7.19)

Now (18) can be rewritten as:

$$\begin{array}{ll} [S \text{ is } \tau_S \supset P] \text{ is } \tau_1; & S \subset \mathcal{U}\,;\, P, P' \subset \mathcal{V} \\ \hline Q(P) \text{ is } \tau_P \text{ and } P'; & \tau_P \subset \mathcal{T} \end{array} \tag{7.20}$$

From (16):

$$\Phi_{\tau P}(y) = \vee_{\chi} \{\Phi_{\tau S}(x) \wedge \text{TFM}[\Phi_1(x,y), \tau 1]\} \quad (7.21)$$

Substituting (17) into (22):

$$\Phi_{\tau S}(x) = x \tan \tau_S = \text{TFM}[(y-x) , \tau_1] = (y-x) \tan \tau_1$$

and $$x = y \tan \tau_1 / [\tan \tau_1 + \tan \tau_S] \quad (7.22)$$

And:

$$\Phi_{\tau P}(y) = y \tan\tau_P = \Phi_{\tau S}(x) = x \tan \tau_S$$

$$= y \tan \tau_1 \tan \tau_S /[\tan \tau_1 + \tan \tau_S]$$

and $$\tan \tau_P = \tan \tau_1 \tan \tau_S /[\tan \tau_1 + \tan \tau_S] \quad (7.23)$$

From (23) and the truth of Q(P) is τ_P:

$$\Phi_{P'}(z) = \text{TFM}(B, \tau_P) = \Phi_P(z) \tan \tau_P = z \tan P \tan \tau_P \quad (7.24)$$

Through use of (20), (23), (24):

$$\Phi_{P'}(z) = z \tan \tau_1 \tan S' \tan \tau_2 \tan P/[\tan S \tan \tau_1 + \tan S' \tan\tau_2] \quad (7.25)$$

Using (24):

$$\boldsymbol{\tan \tau_P = \tan \tau_1 \tan S' \tan \tau_2 / [\tan S \tan\tau_1 + \tan S' \tan \tau_2]} \quad \textbf{(7.26)}$$

From (24):

$\tan P' = \tan P \tan \tau_P$

$P' = \tan^{-1}[\tan P \tan \tau_P]$ **(7.27)**

7.6 Examples

An example of this modus ponens deduction is as follows:

If the amount of local materials is Many (M), then the piles are Sustainable (S), this is True (TR).

If it is True (TR) that the amount of local materials is Fairly Many (FM), what is the conclusion?

[Amount is M ⊃ Piles are S] is TR

[Amount is FM] is TR

Q (Piles are S) = τ_P and piles are P'

Using equation (26) and the values from Table 7.1:

$\tan \tau_P = \tan(TR) \tan(FM) \tan(TR) / [\tan(M) \tan(TR) + \tan(FM) \tan(TR)]$

$= 16.8^o$

and (27):

$P' = \tan^{-1}[\tan P \tan \tau_P]$

$= 16.32^o$

Rule: If the amount of local materials is 'Many', then the piles are 'Sustainable'.

Fact: The amount of local materials is 'Fairly Many'.

Result: The piles are 'Less Than Fairly Sustainable'.

In the previous example, the values of τ_1 and τ_2 are fixed as 'True', or 45º. The user is not able to adjust these values, as they are set at a 'safe' value, which will not affect the final result significantly. However, there is a set of circumstances under which these values will not work. For example:

Example 1:

If the amount of local materials is Many (M), then the piles are Sustainable (S), this is True (TR).

If it is True (TR) that the amount of local materials is Few (F), what is the conclusion?

[Amount is M ⊃ Piles are S] is TR

[Amount is F] is TR

Q (Piles are S) = τ_P and piles are P'

$$\tan \tau_P = \tan(TR) \tan(F) \tan(TR) / [\tan(M) \tan(TR) + \tan(F) \tan(TR)]$$

$$= \tan(45^\circ) \tan(-45^\circ) \tan(45^\circ) / [\tan(45^\circ) \tan(45^\circ) + \tan(-45^\circ) \tan(45^\circ)]$$

$= -1 / 0$

In this situation, the denominator is equal to zero, and thus the answer is *Undefined*.

Example 2:

If the amount of local materials is Many (M), then the piles are Sustainable (S), this is True (TR).

If it is True (TR) that the amount of local materials is Very Few (VF), what is the conclusion?

[Amount is M ⊃ Piles are S] is TR

[Amount is VF] is TR

Q (Piles are S) = τ_P and piles are P'

$$\tan \tau_P = \tan (TR) \tan (VF) \tan (TR) / [\tan (M) \tan(TR) + \tan (VF) \tan (TR)]$$

$$= \tan (45^o) \tan (-67.5^o) \tan (45^o) / [\tan(45^o) \tan(45^o) + \tan(-67.5^o) \tan(45^o)]$$

$$= 97.8$$

$$P' = \tan^{-1}[\tan P \tan \tau_P]$$

$$= \tan^{-1}[\tan 45^o \tan 97.8^o]$$

$$= 59.6^o$$

Now, this situation did not produce an 'undetermined' answer, as in the previous example. However, this answer does not make logical sense. The rule states that 'If the amount of local materials is Many (M), then the piles are Sustainable (S). τ_1 = True (TR). The fact is given as 'The amount of local materials is Very Few (VF)'. Most people, without any background in fuzzy logic could determine the final answer here should in fact be negative as well. The equation, however, gives an answer of 59.6º, or 'Between Sustainable and Very Sustainable'.

In situations such as these, a special case must be made. By setting τ_1 set equal to 'Absolutely True' (AT) in *Example 1A*:

[Amount is M ⊃ Piles are S] is AT

[Amount is F] is TR

Q (Piles are S) = τ_P and piles are P'

$$\tan \tau_P = \operatorname*{Limit}_{AT \to \Pi/2} \frac{\tan (AT) \tan (F) \tan (TR)}{[\tan (M) \tan(AT) + \tan (F) \tan (TR)]}$$

$$= -54.2$$

$$P' = \tan^{-1}[\tan P \tan \tau_P]$$

$$= -43.4^{\circ}$$

The result now makes sense, as it is correlates to 'Unsustainable'.

And *Example 2A*:

If the amount of local materials is Many (M), then the piles are Sustainable (S), this is Absolutely True (AT).

If it is True (TR) that the amount of local materials is Very Few (VF), what is the conclusion?

[Amount is M $\supset$ Piles are S] is AT

[Amount is VF] is TR

Q (Piles are S) = τ_P and piles are P'

$$\tan \tau_P = \operatorname*{Limit}_{AT \to \Pi/2} \frac{\tan(AT)\tan(VF)\tan(TR)}{[\tan(M)\tan(AT) + \tan(VF)\tan(TR)]}$$

$$= -121.4$$

$$P' = \tan^{-1}[\tan P \tan \tau_P]$$

$$= -64.7^{\circ}$$

The result has gone from 'Between Sustainable and Very Sustainable' to 'Very Unsustainable'.

7.7 Software Program

A program was written in order to take a user-defined rule and condition and give a graphical answer. As in the Rotational Model in Chapter 6, the user defines the rule by inputting a value for S (amount of local materials in the concrete piles) and P (sustainability of piles). In the example (Figure 7.4) the user has defined the rule as: If the amount of local materials is '*Many*', then the piles are '*Sustainable*'. This rule will vary, depending on the 'expert' or knowledge engineer, and the conditions of the project.

Next, the condition is entered. This is simply the amount of local materials being planned for the pile foundation project. In this example, the user has inputted the amount of local materials is '*Fairly Many'*.

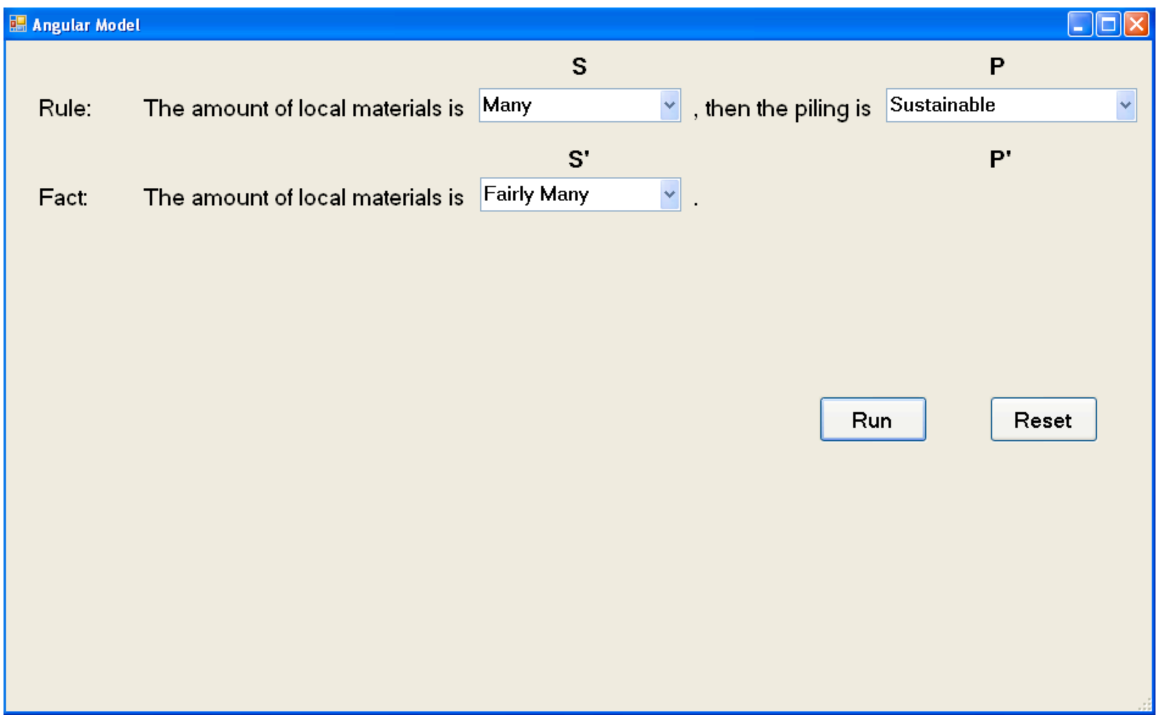


Figure 7.4: Angular Model Program - User Input

The final result is given in numerical, graphical, and linguistic format in Figure 7.5. The final angle (seen by the green arrow) is 16.32º. This angle corresponds to a sustainability of '*Less than fairly sustainable'*.

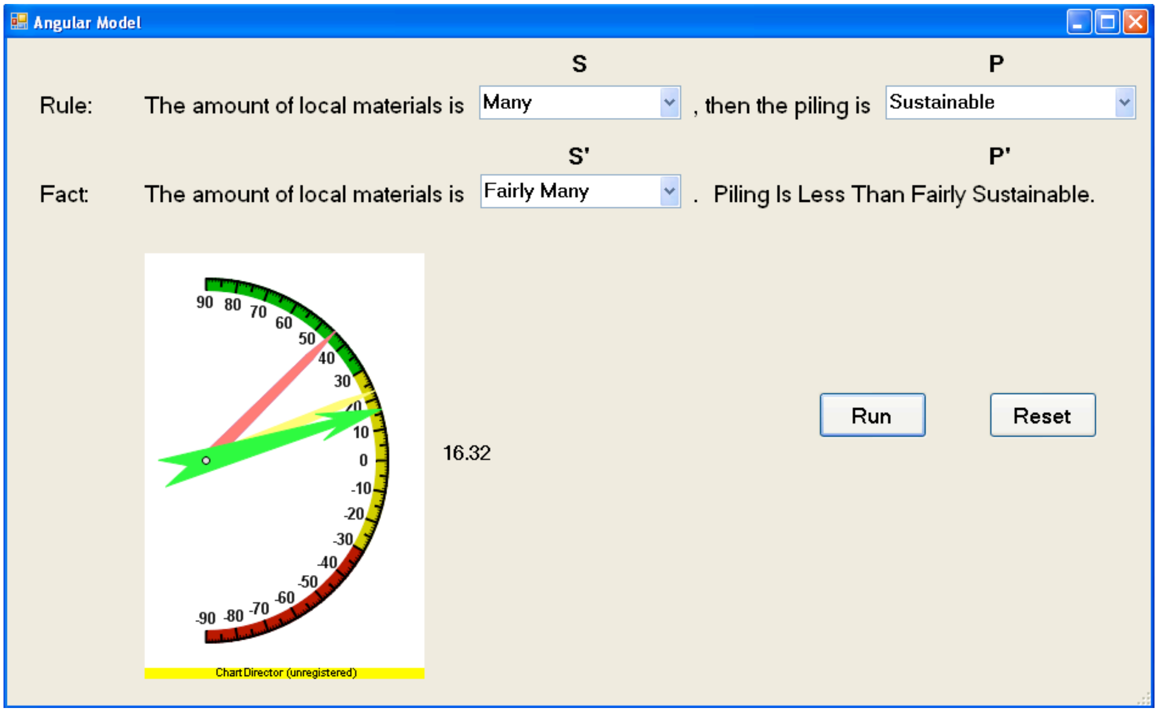


Figure 7.5: Angular Model Program - Final Result

Additional examples of the Angular Model using the Modus Ponens Deduction can be found in Appendix A.

CHAPTER 8 : MODEL COMPARISON, RESULTS OF THE STUDY

8.1 Triangular Model

The Triangular Model is different from the other models presented. The input variable is the same as the output (Figure 8.1). The model depends on knowledgeable experts who, weighing their experience, give a determination of sustainability. This model depends heavily on whatever these experts' view about sustainability. This model will not be directly compared to the other four models.

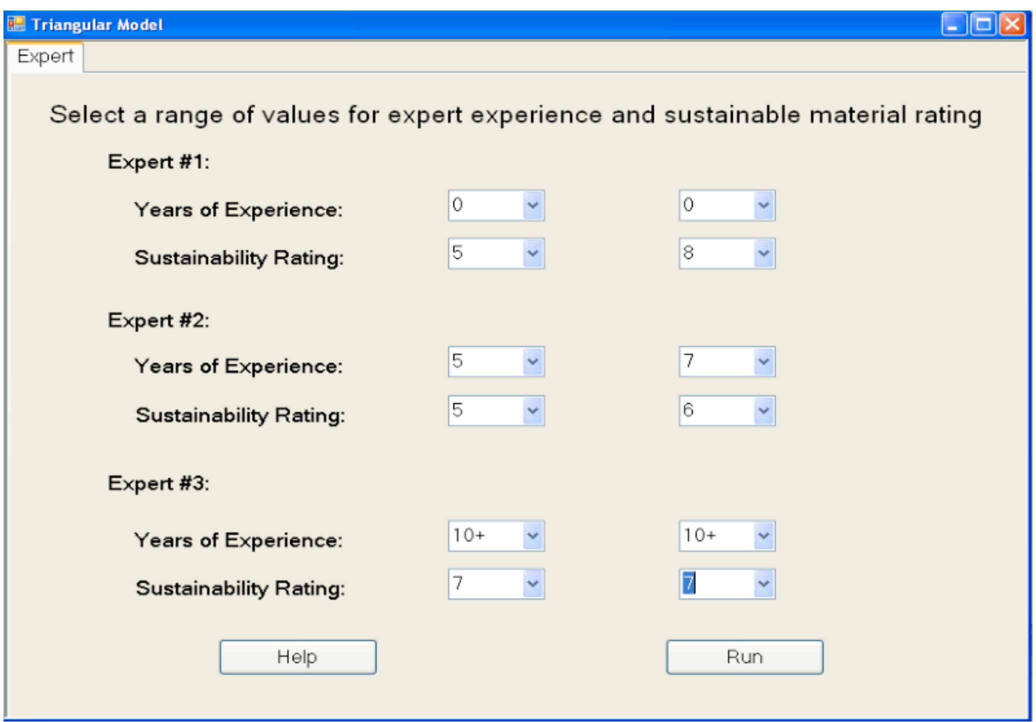


Figure 8.1: Triangular Model Input

This model would be best used as a way to determine rules for the subsequent models. For example, in the Mamdani Model, the author supplied a table of rules for Practicality vs. Consequence, ad Cost vs. Consequence. However, using a survey along with the triangular model, new rules could be applied to this model. The model would need to be expanded to accommodate larger numbers of people, but could prove to be a very effective tool.

The model is effective because it gives the result in many forms. There is a graphical output, linguistic, and numerical (Figure 8.2). With a high-level user, more information is given. However, to a user not familiar with ‘Rt’ and ‘I’, an easy to read linguistic variable in given.

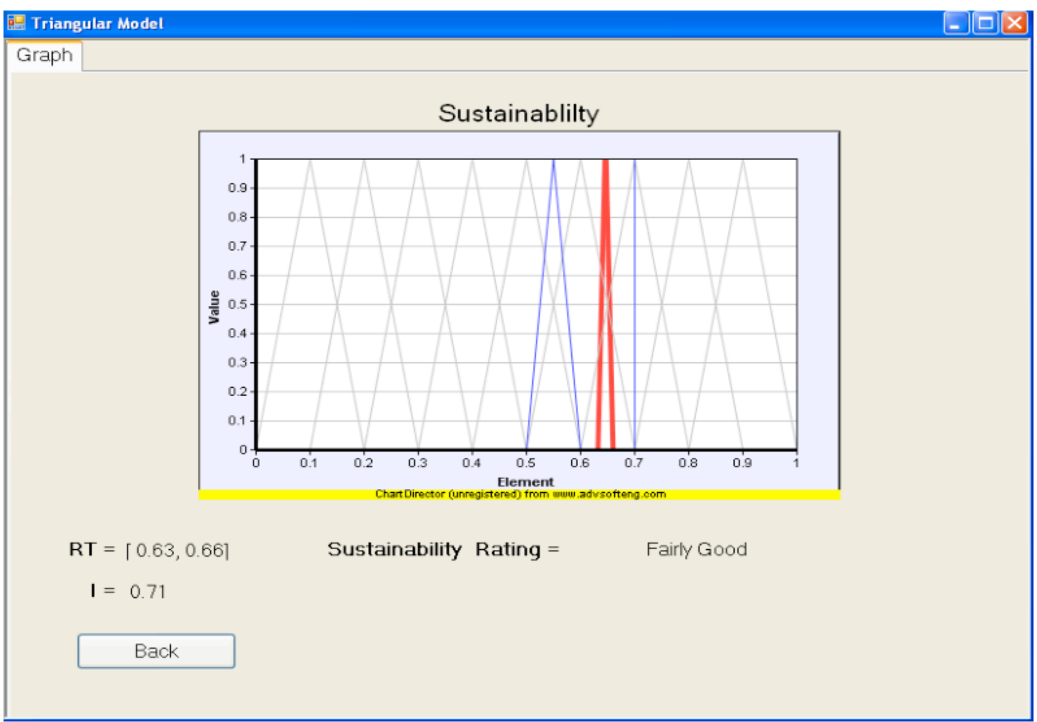


Figure 8.2: Triangular Model Output

8.2 Translational Model

The main advantage of the Translational Model is that the user is able to enter a variety of detailed information to determine the sustainability of the project (Figure 8.3). The model is user-friendly to users that are not engineers, as they are not required to determine the rules themselves.

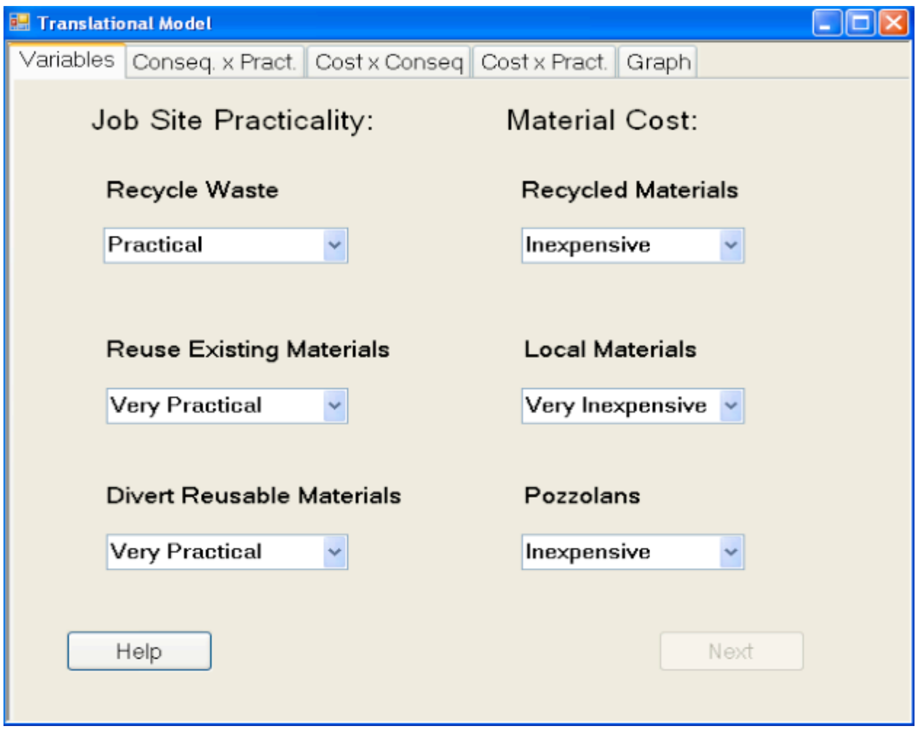


Figure 8.3: Translational Model Input

Additionally, if an expert user feels there has been an error, he/she is able to access the three matrices to understand the logic behind the model (Figure 8.4).

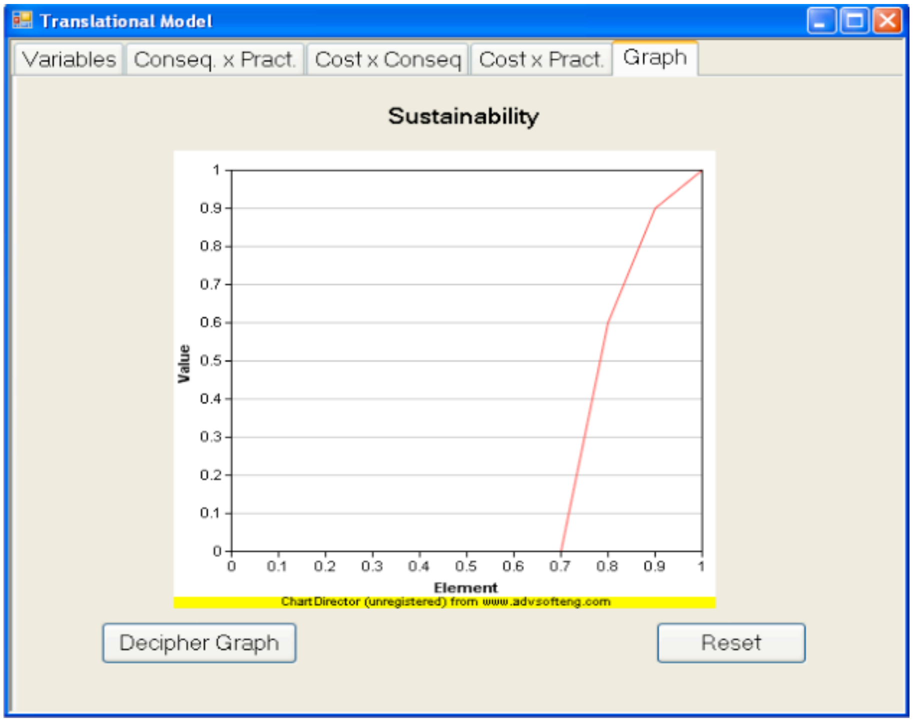


Figure 8.4: Translational Model Output

A disadvantage of the Translational Model is that while there are many inputs to consider, these inputs may not be the most optimal for a certain project. The user may not have the information required for a certain variable, and would like to add a separate variable. This is not possible in this model. Additionally, the membership functions may not be ideal for that certain situation, and are not able to be changed by the user.

8.3 Mamdani Model

The Mamdani Model is fairly user friendly in its logic. It gives an easy to read 'If A and B then C' model, which is appealing to beginner users (Figure 8.5).

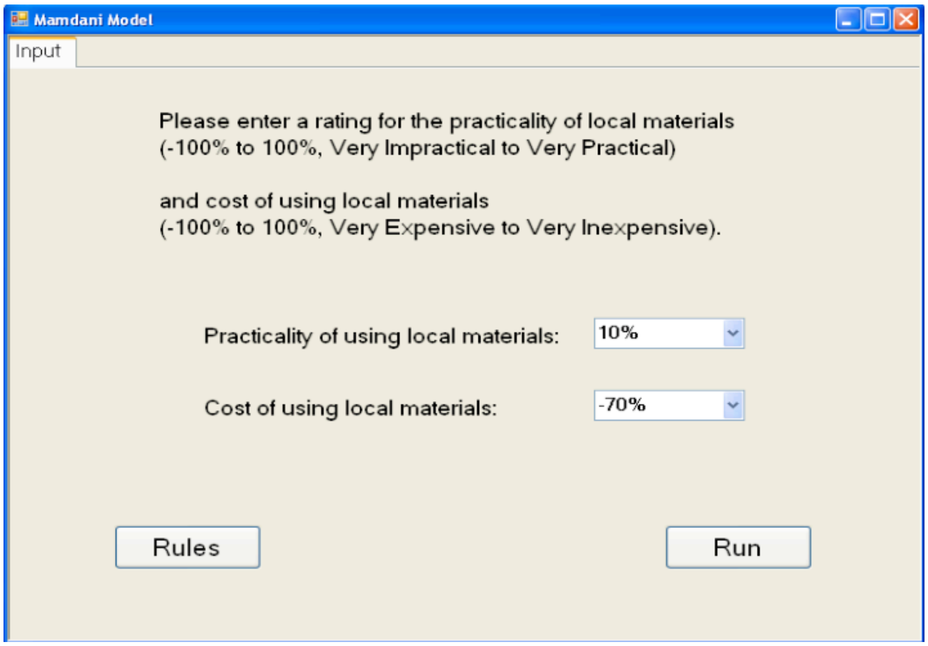


Figure 8.5: Mamdani Model Input

Additionally, the steps to the answer are shown, as the four graphs on the left of Figure 8.6. The user also gets a graphical representation of the final sustainability, as well as an I value, and a linguistic term. This model, like the Triangular Model, is easy to read as a beginner user, while giving additional information to expert users.

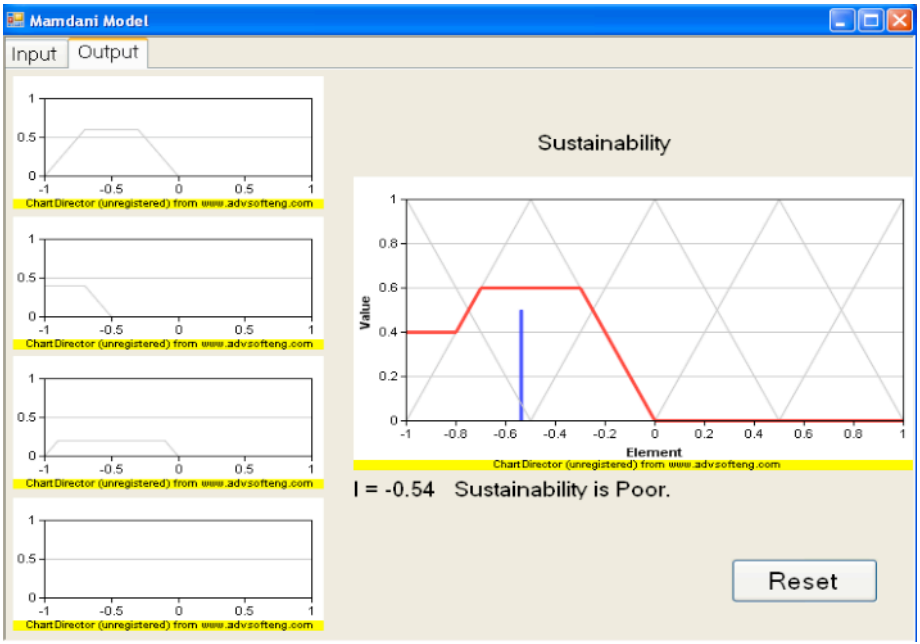


Figure 8.6: Mamdani Model Output

8.4 Rotational and Angular Model

Both the Rotational and Angular Models employ a modus ponens rule base in the interface (Figure 8.7). The advantage to this feature, for an expert user, is the ability to set the circumstances of the model without reprogramming. However, beginner users may not be able to understand this feature, since an incorrectly entered rule may have a dramatic effect on the final result.

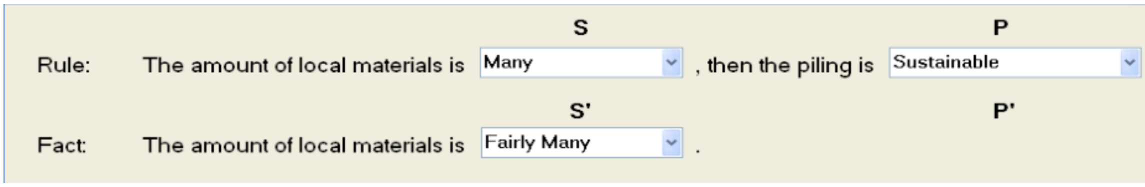


Figure 8.7: Modus Ponens Interface

The advantage to using the Rotational Model is that each graph, ITFM, LIR, and TFM is shown, guiding the user through the logic of the model. The model does not, however, give a crisp answer. The user must defuzzify the final value of P’ himself/herself, using the guide of Baldwin’s Truth-values. This makes this model much less user friendly.

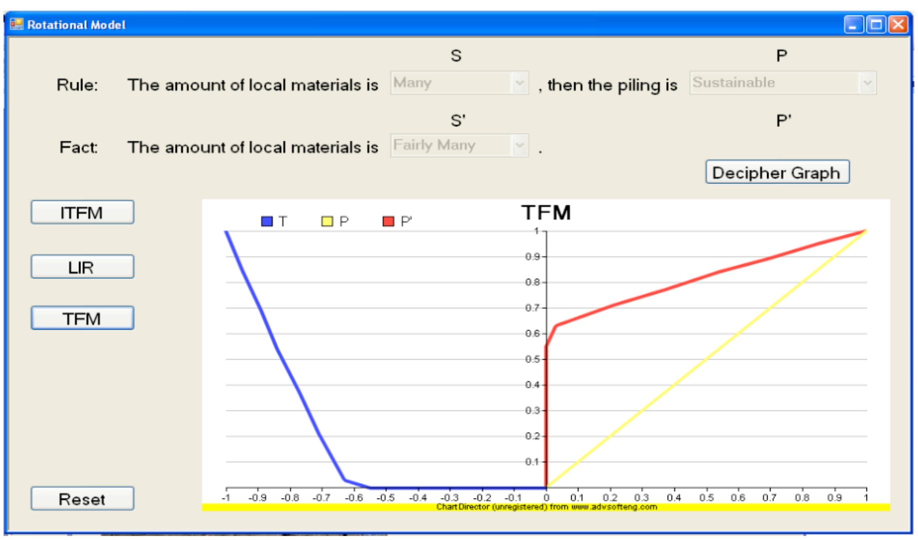


Figure 8.8: Rotational Model Output

Additionally, the Rotational Model does not allow S and S' to be 'opposites'. That is, if S is positive, and S' is negative (or vice versa), the result will be undefined (Figure 8.9).

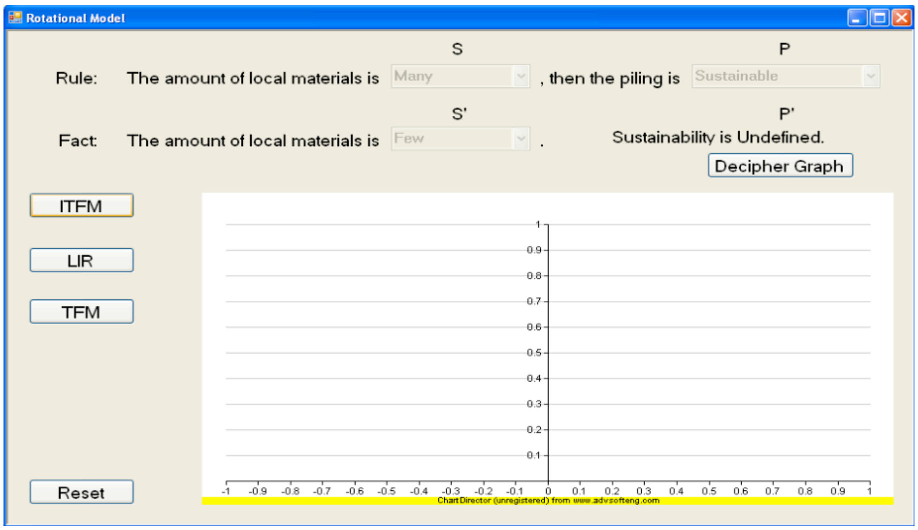


Figure 8.9: Rotational Model Undefined Answer

The Angular Model, on the other hand, gives graphical, numerical, and linguistic answers to define the sustainability (Figure 8.10).

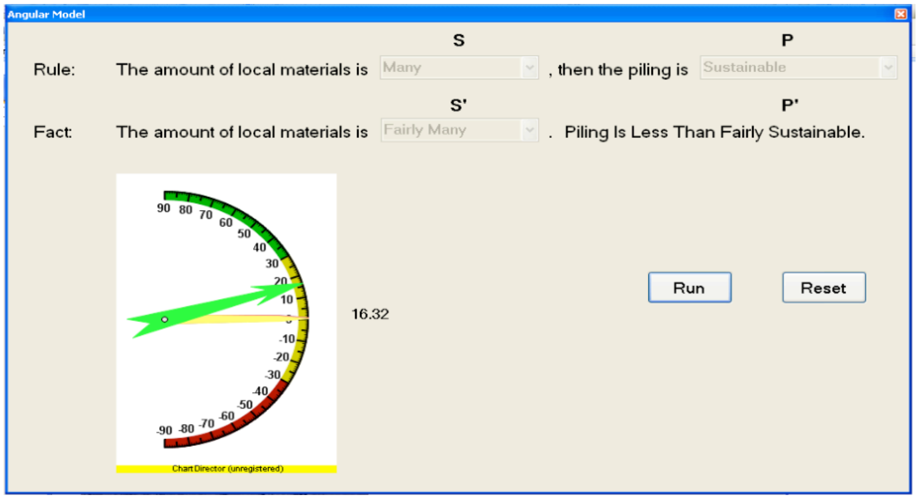


Figure 8.10: Angular Model Output

The Angular Model also is able to handle answers with 'opposite' values of S and S' (Figure 8.11). Using the previous example:

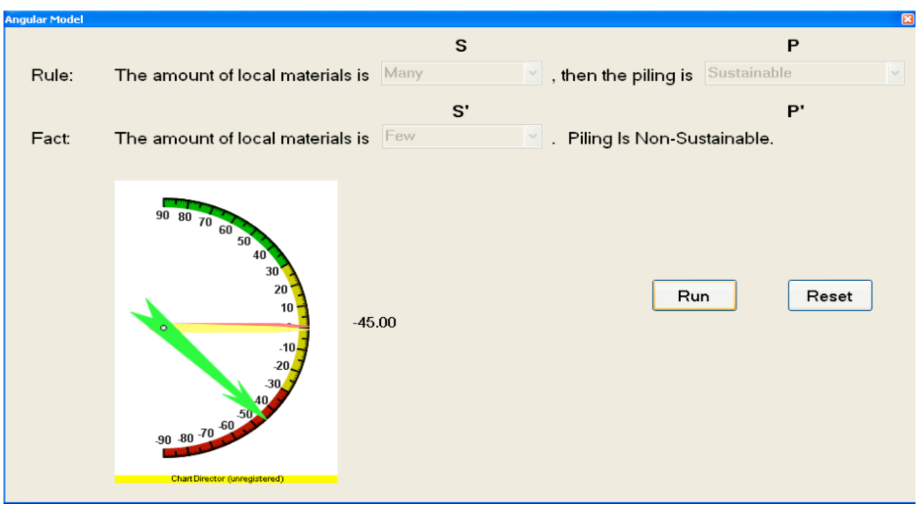


Figure 8.11: Angular Model, Opposite S and S' Input Example

8.5 Best Model

While each user may prefer a different model for a specific project, the author has picked the combination of Triangular and Mamdani models as the most effective in this case. The Triangular model will be used to fill in the rules of the Mamdani approach. The user should be a knowledge engineer or expert. They will be required to survey a number of experts to set the rules for the Mamdani model. The Mamdani model allows the user to assess two separate variables at a time. The model display graphical, numerical, and linguistic variables for any level user to utilize. The following is an example:

The (hypothetical) experts are given the following hypothetical scenario:

The cost is ‘Positive’ (or ‘Low’) and the Practicality is ‘Moderate’. What is the sustainability? The experts’ answer in Figure 8.12.

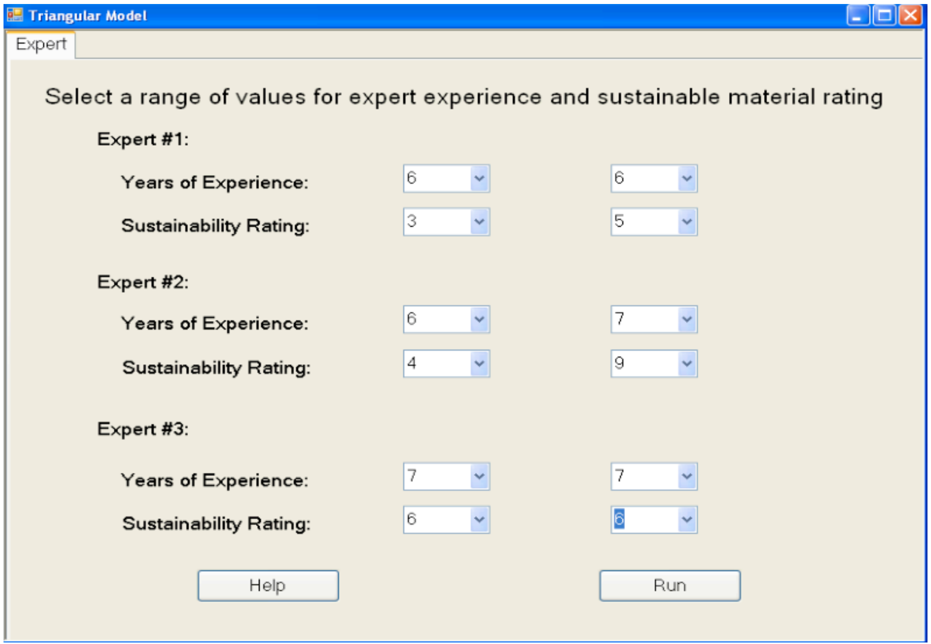


Figure 8.12: Triangular Model Expert Input

The final result is 'Fair', in Figure 8.13. This value is then transferred to the table of rules, in Table 8.1.

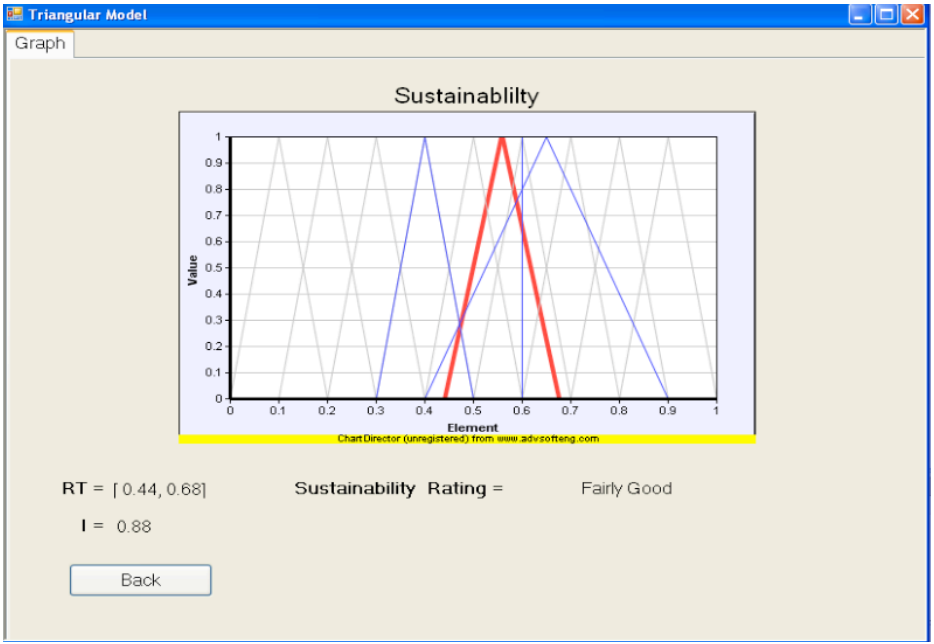


Figure 8.13: Triangular Model Sustainability

		Cost				
	Sustainability	**Negative**	**Fairly Negative**	**Moderate**	**Fairly Positive**	**Positive**
Practicality	**Negative**	Negative	Negative	Negative	Negative	Negative
	Fairly Negative	Negative	Fairly Negative	Fairly Negative	Fairly Negative	Fairly Negative
	Moderate	Negative	Fairly Negative	Moderate	Moderate	Moderate
	Fairly Positive	Negative	Fairly Negative	Moderate	Fairly Positive	Fairly Positive
	Positive	Negative	Fairly Negative	Moderate	Fairly Positive	Positive

Table 8.1: Mamdani Model Rules Decision

These rules are then implemented in the Mamdani Model. The user is now confronted with the situation of choosing the practicality and cost values, in Figure 8.14. The chosen values are a 'moderate' cost and 'fairly negative' practicality .

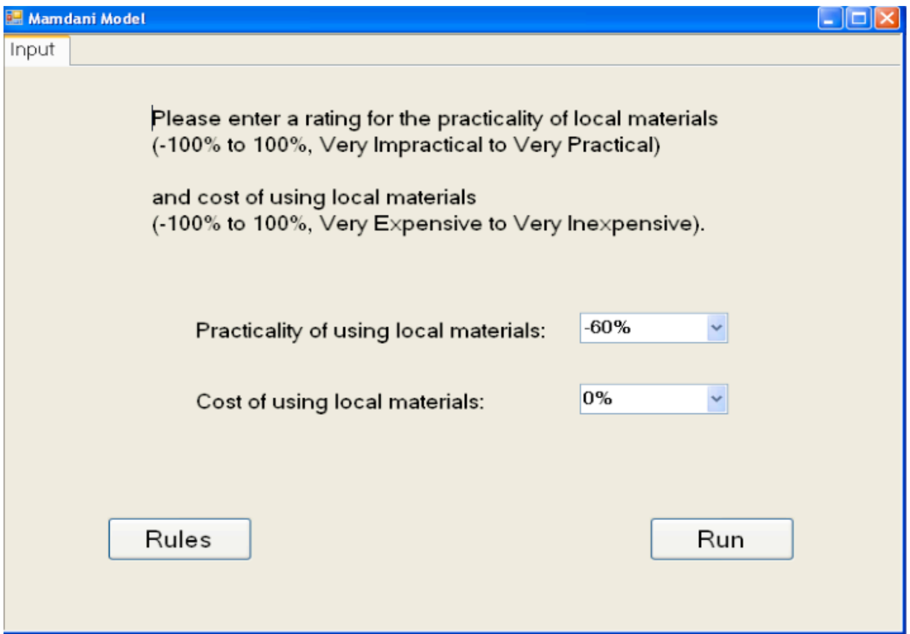


Figure 8.14: Mamdani Model User Input

Figure 8.15 gives the result as 'Poor' sustainability.

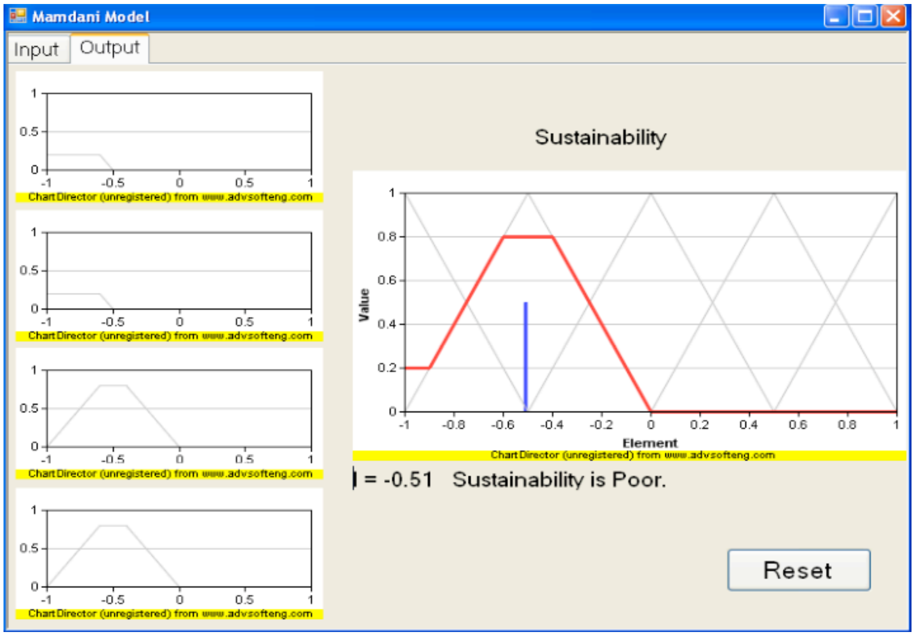


Figure 8.15: Mamdani Model Sustainability

8.6 Conclusions

The combination of the Triangular and Mamdani Models attempts to put the focus on foundations as a source of sustainable building. This system is geared towards drawing attention to concrete piles as not simply the foundation of the building, but an opportunity to bring sustainability into the project.

The Triangular Model can be used in tandem with a survey of many experts, greater than the small number of three given here. Because of the conservative values given in the rules table, and the varying environments across the country and the world, the membership functions must be studied to determine which is best for the region where the project is located.

The Mamdani Model employs only two inputs in this thesis. However, the model allows for expansion. Given the option to bring additional variables into the determination may be beneficial in the decision-making process.

These two models together can be used within a decision-making framework during design and construction. Being able to accommodate owners with a certain level of sustainability while maintaining certain cost or practicality restraints is important to the betterment of the industry.

CHAPTER 9 : SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

9.1 Summary

Sustainability has become a way of the construction industry in the last decade. The use of concrete piles, however, has had an adverse effect on the environment. Cement has a large amount of embodied energy, and releases a significant amount of carbon dioxide into the environment in production. Substitutions such as recycled materials, local materials, and pozzolans are one way of reducing these harmful effects, and increasing the sustainability.

With an imprecise variable like sustainability, fuzzy logic must be employed, using imprecise input values, in order to approximate an answer. Five models are used in this study.

The first model is the Triangular model. The model uses expert information, such as an opinion on sustainability, along with years of experience. The model uses equations to give a graphical result. This result is a triangular graph, which is matched to a given graph of linguistic variables. This model is useful in determining rules for other models, like Mamdani.

The second, the Translational model, uses variables pertaining to practicality and cost. These variables are broken down into three jobsite practices and material modifications. The result is determined by manipulating membership functions, using matrices and giving a graphical result.

The third model used is the Mamdani approach. Mamdani uses numerical variables (-100 to 100) for practicality and cost. These variables are mapped to membership functions, and using a 'max of mins' method, determines a graphical result. The centroid method is used to determine a final linguistic determination of sustainability.

The fourth model is the Rotational Model. This employs the modus ponens deduction. The user enters both a rule and fact, with variables of 'amount of local materials' and sustainability. The result is given as a graph, which can be compared to Baldwin's Truth values.

The fifth and final model is the Angular Model. Similar to the Rotational model, it employs the modus ponens deduction, using the variables 'amount of local materials' and sustainability. The result, however, is an angle, which is compared to a given set of rules to give a linguistic result.

It should be noted that the models employed in this thesis focus on increasing and assessing the sustainability of the piles, and not assessing the functionality or stress and strain qualities of the piles in general.

9.2 Conclusions

This study has discussed the varying nature of sustainable construction. It has given modifications that affect sustainability in terms of practicality and cost. These factors are important to research, in order to understand what variables can be used in the various models employed.

These models inferred:

- Triangular

  A model based on expert opinions. This model weights expert opinions based on years of experience. It would be best used in conjunction with other models to determine membership functions.

- Translational

  A more expansive model than the rest, this model is user-friendly to beginner users. However, its many variables may not always be optimal or known, and they cannot be changed.

- Mamdani

  A user-friendly model that also provides additional information helpful to expert users.

- Rotational

  A model that illustrates the modus ponens deduction. The output result, however, is up to the user's interpretation.

- Angular

Another model that illustrates the modus ponens deduction. The output, in this case, gives graphical, numerical, and linguistic results. The input rule, however, may be intimidating to beginner users.

The models were discussed in detail individually, and then compared to one another. Finally, a 'best-fit' model was chosen as a combination of the Triangular and Mamdani models. The Triangular model was deemed necessary in order to improve the rules built in to the Mamdani model. A survey of experts would be required to fill in the table of rules. The Mamdani approach allows users to assess two different variables at a time, while giving a graphical, numerical, and linguistic result. The model also allows expert users to see the math behind the program, by supplying four additional graphs.

9.3 Recommendations

Several recommendations can be made based on the models built:

- Test the models using different membership functions.

- Allow the user to adjust the membership functions to find those that fit best.

- Expand the models to include additional variables that affect sustainability.

- Test the models on actual planned construction projects.

- Conduct a survey to fill in rules for Mamdani model.

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APPENDIX A: ADDITIONAL EXAMPLES

Triangular Model:

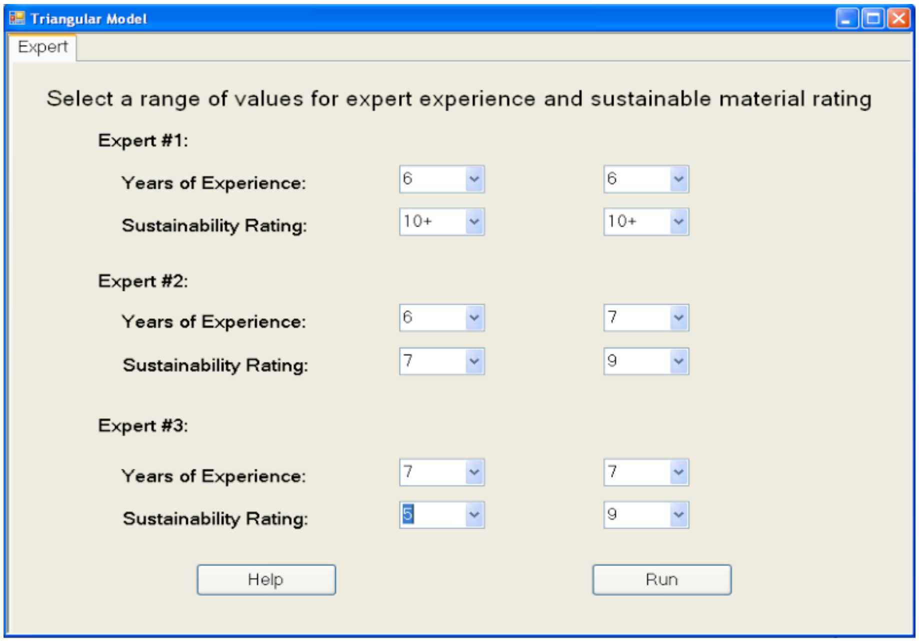


Figure A.1: Triangular Model – User Input - Example 1

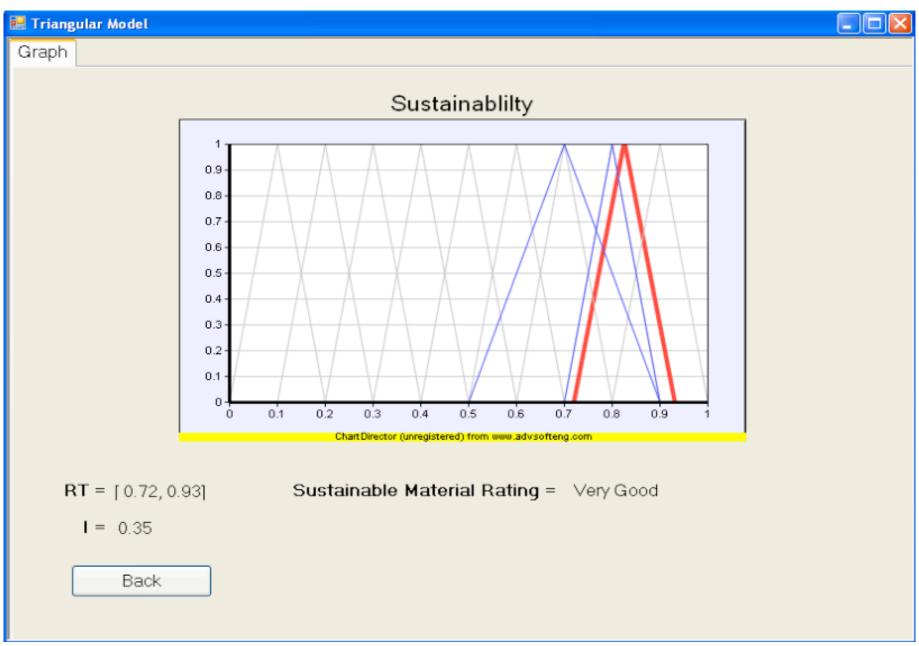


Figure A.2: Triangular Model – Sustainability Graph - Example 1

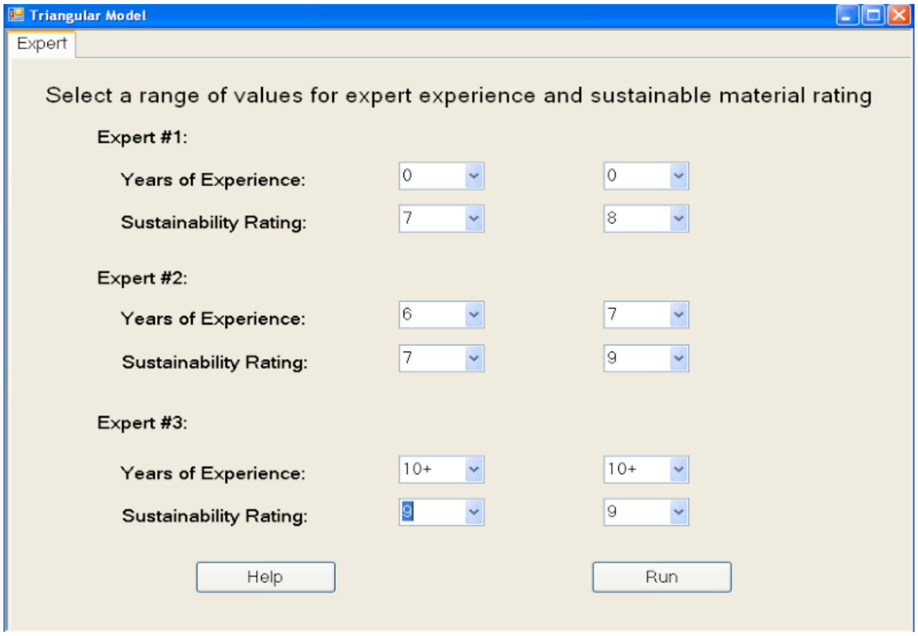


Figure A.3: Triangular Model – User Input - Example 2

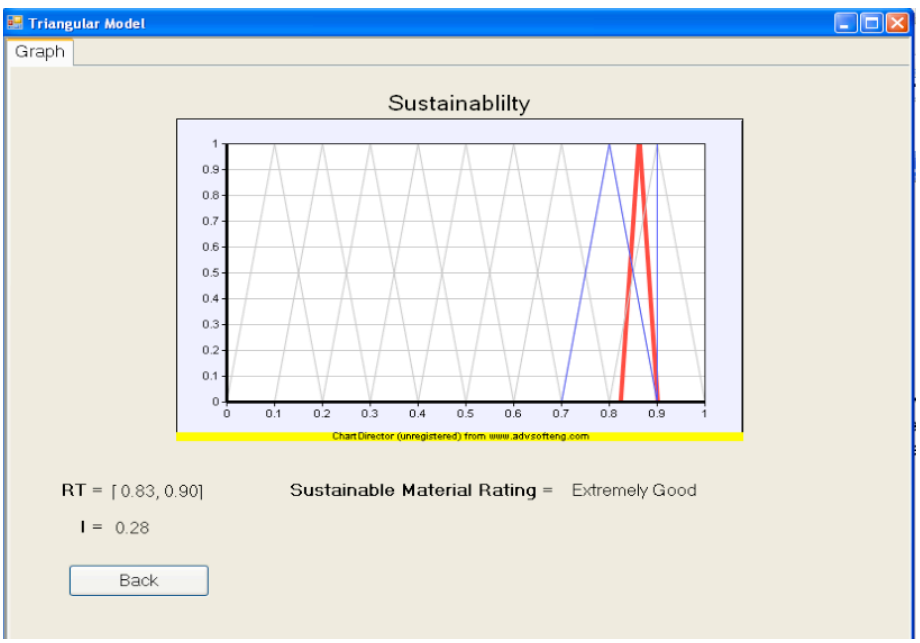


Figure A.4: Triangular Model – Sustainability Graph - Example 2

Translational Model:

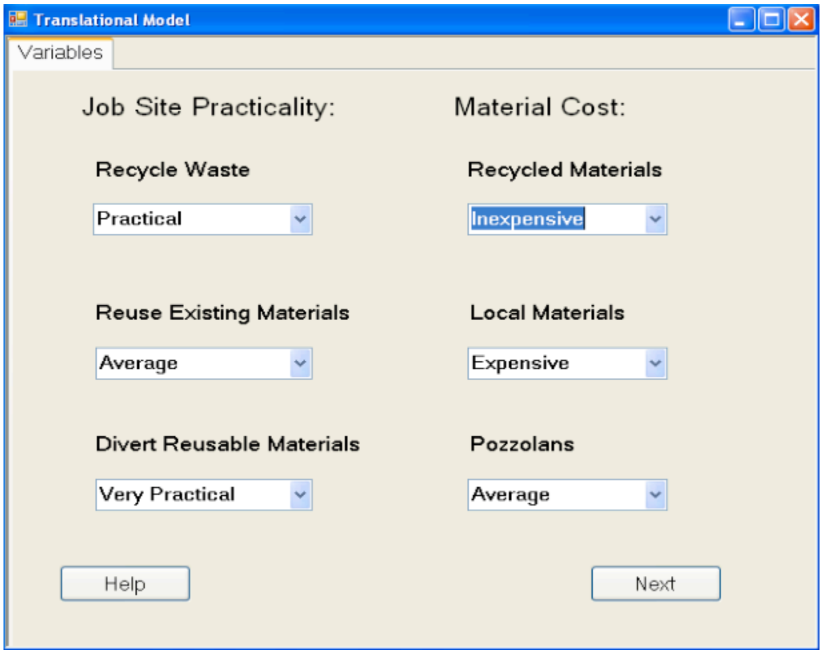


Figure A.5: Translational Model – User Input - Example 1

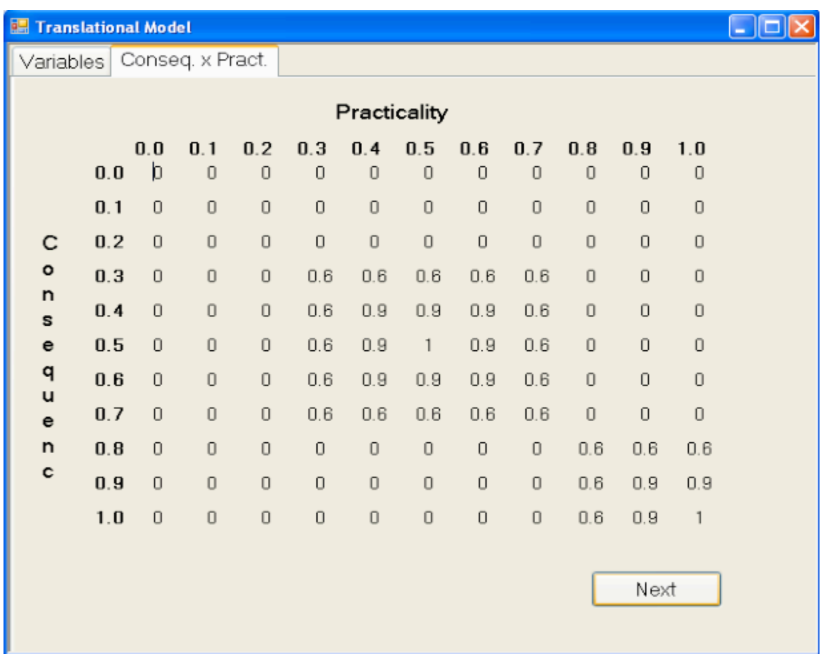
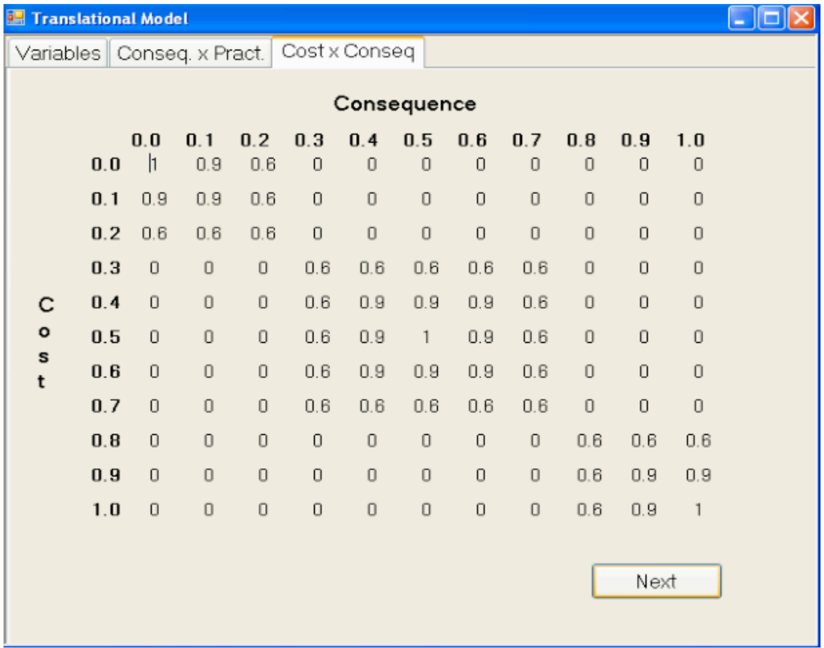
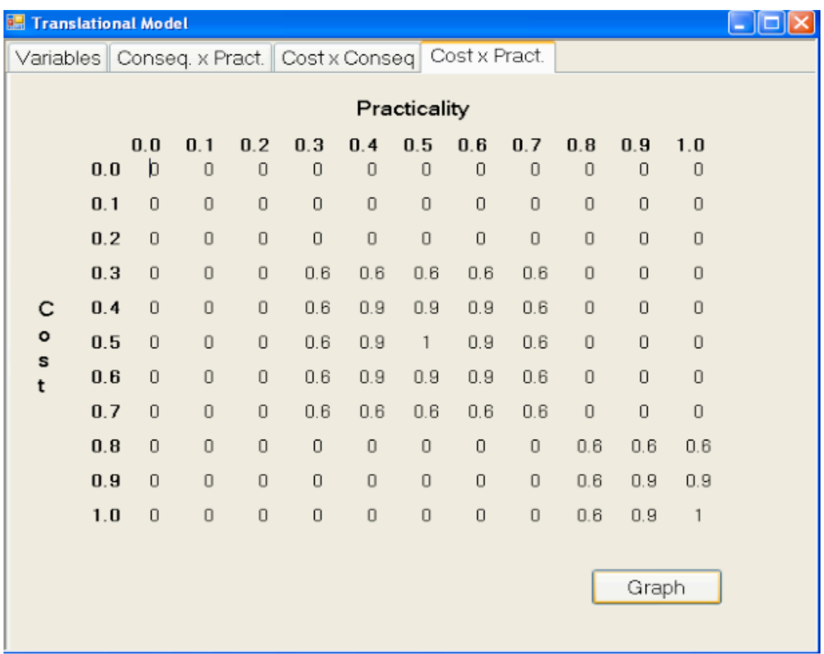


Figure A.6: Translational Model – Matrix 1 - Example 1



Cost	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
0.0	1	0.9	0.6	0	0	0	0	0	0	0	0
0.1	0.9	0.9	0.6	0	0	0	0	0	0	0	0
0.2	0.6	0.6	0.6	0	0	0	0	0	0	0	0
0.3	0	0	0	0.6	0.6	0.6	0.6	0.6	0	0	0
0.4	0	0	0	0.6	0.9	0.9	0.9	0.6	0	0	0
0.5	0	0	0	0.6	0.9	1	0.9	0.6	0	0	0
0.6	0	0	0	0.6	0.9	0.9	0.9	0.6	0	0	0
0.7	0	0	0	0.6	0.6	0.6	0.6	0.6	0	0	0
0.8	0	0	0	0	0	0	0	0	0.6	0.6	0.6
0.9	0	0	0	0	0	0	0	0	0.6	0.9	0.9
1.0	0	0	0	0	0	0	0	0	0.6	0.9	1

Figure A.7: Translational Model – Matrix 2 - Example 1



Cost	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
0.0	0	0	0	0	0	0	0	0	0	0	0
0.1	0	0	0	0	0	0	0	0	0	0	0
0.2	0	0	0	0	0	0	0	0	0	0	0
0.3	0	0	0	0.6	0.6	0.6	0.6	0.6	0	0	0
0.4	0	0	0	0.6	0.9	0.9	0.9	0.6	0	0	0
0.5	0	0	0	0.6	0.9	1	0.9	0.6	0	0	0
0.6	0	0	0	0.6	0.9	0.9	0.9	0.6	0	0	0
0.7	0	0	0	0.6	0.6	0.6	0.6	0.6	0	0	0
0.8	0	0	0	0	0	0	0	0	0.6	0.6	0.6
0.9	0	0	0	0	0	0	0	0	0.6	0.9	0.9
1.0	0	0	0	0	0	0	0	0	0.6	0.9	1

Figure A.8 Translational Model – Matrix 3 - Example 1

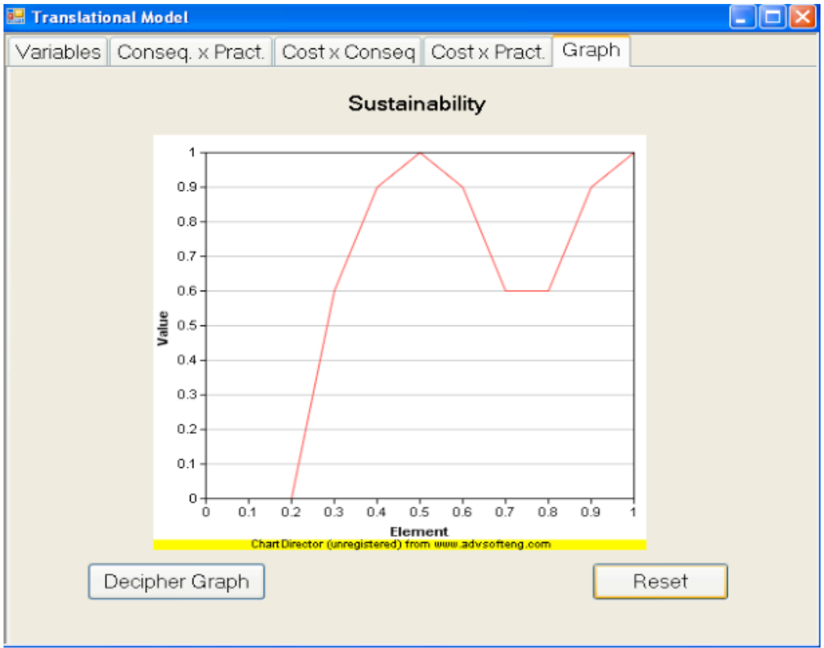


Figure A.9: Translational Model – Sustainability Graph - Example 1

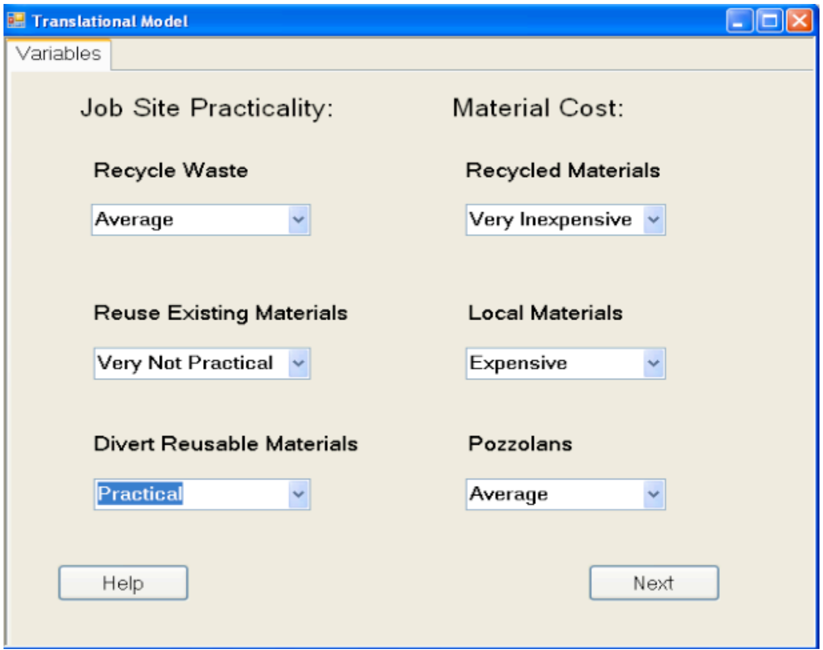


Figure A.10: Translational Model – User Input - Example 2

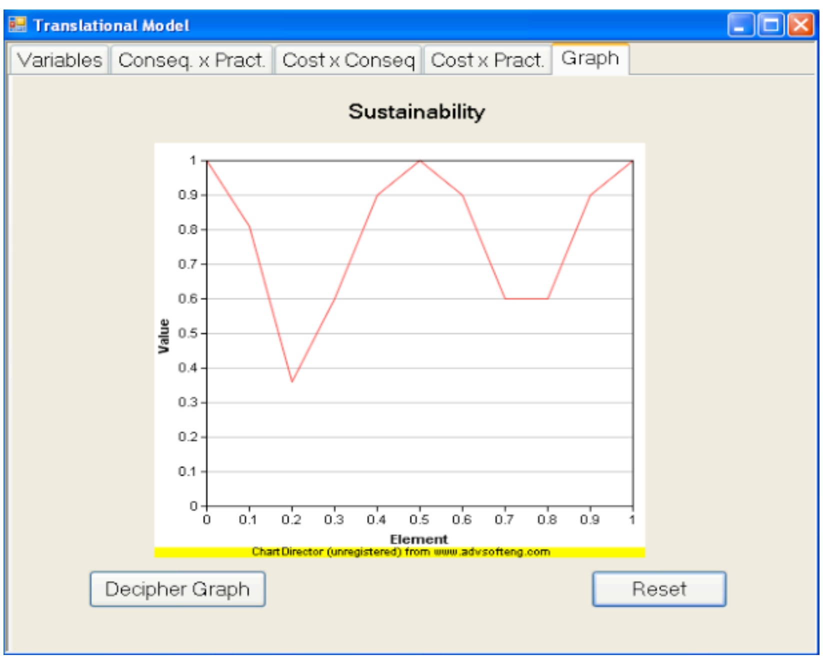


Figure A.11: Translational Model – Sustainability Graph - Example 2

Mamdani Model:

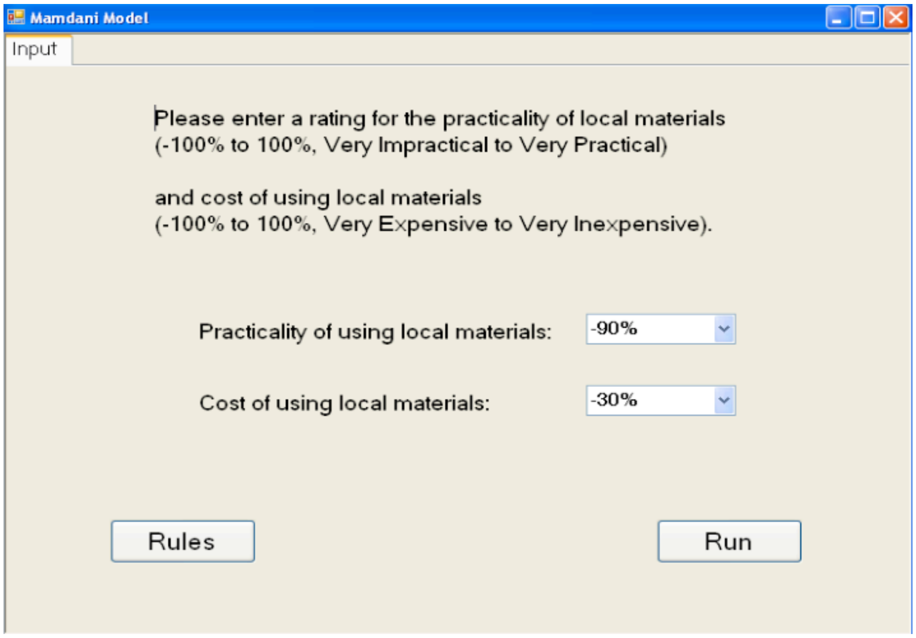


Figure A.12: Mamdani Model – User Input - Example 1

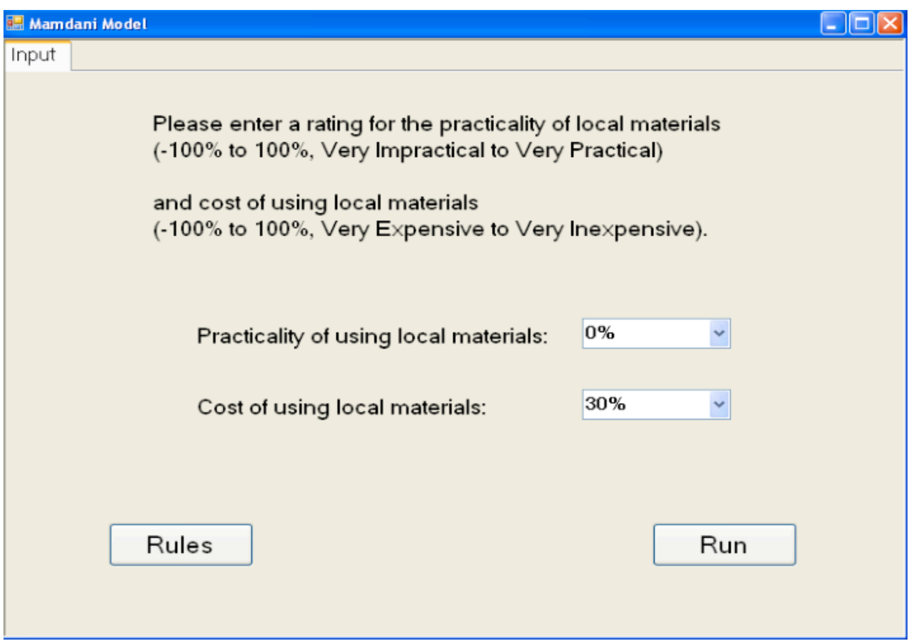


Figure A.13: Mamdani Model – Sustainability Graph - Example 1

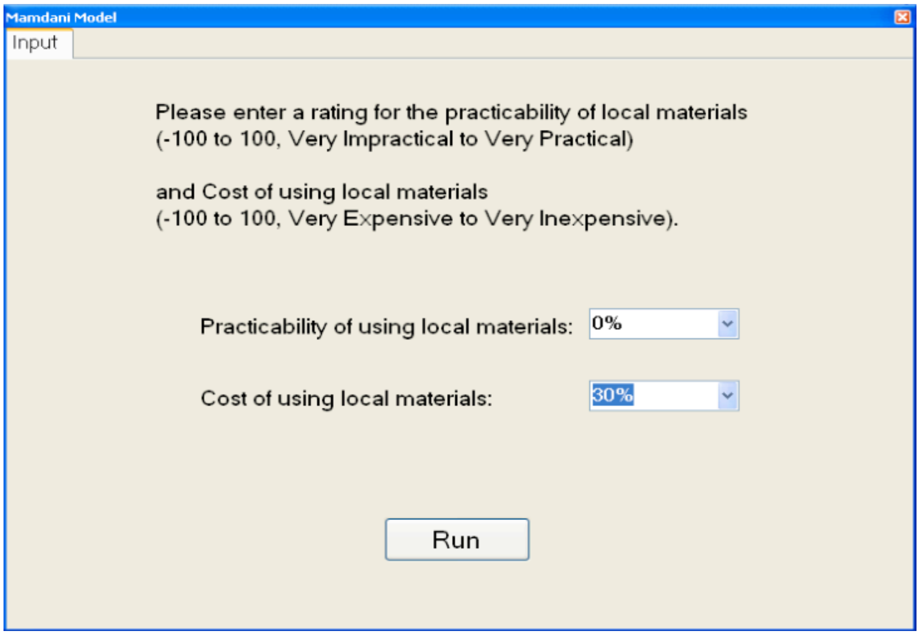


Figure A.14: Mamdani Model – User Input - Example 2

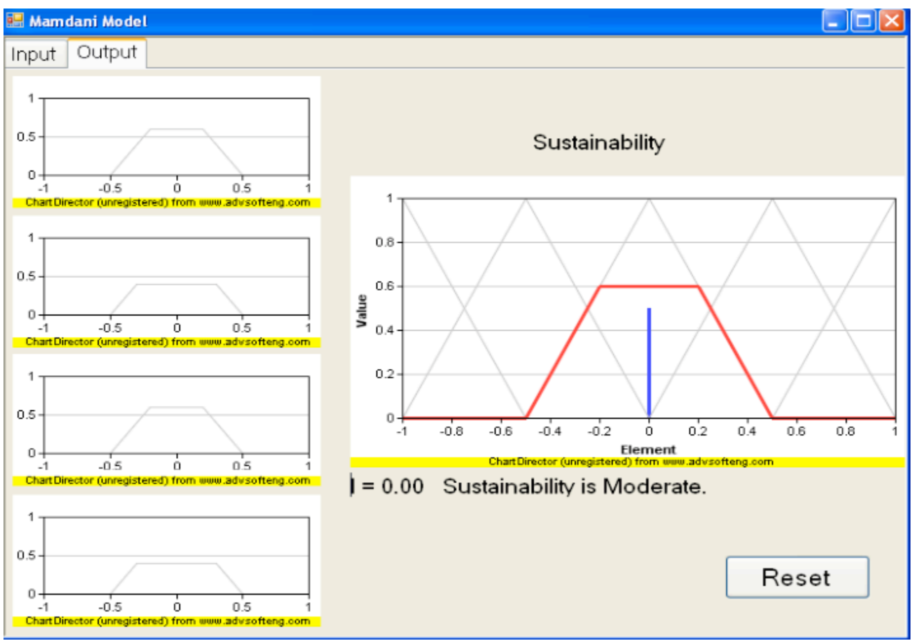


Figure A.15: Mamdani Model – Sustainability Graph - Example 2

Rotational Model:

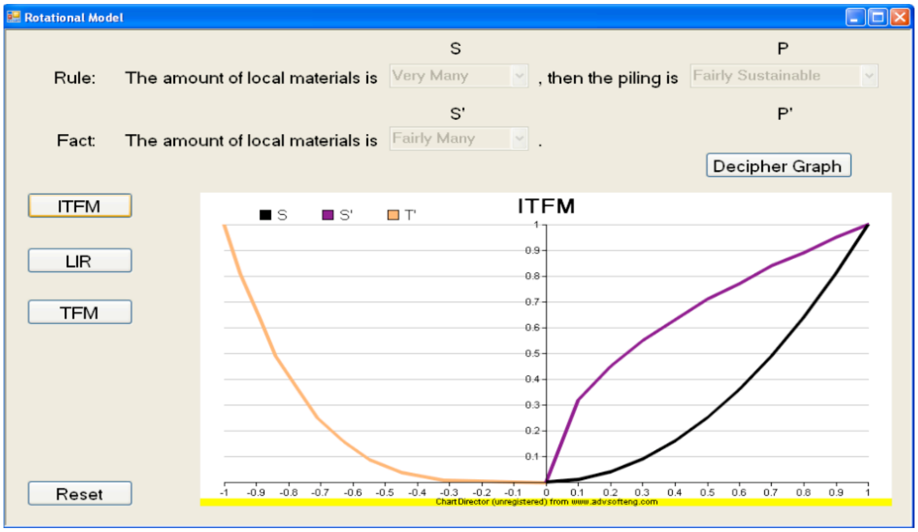


Figure A.16: Rotational Model – ITFM Graph - Example 1

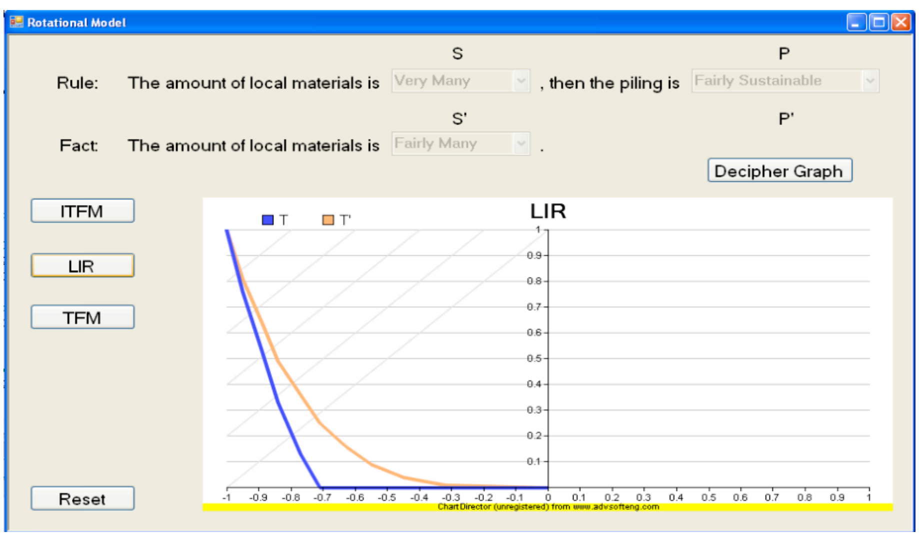


Figure A.17: Rotational Model – LIR Graph - Example 1

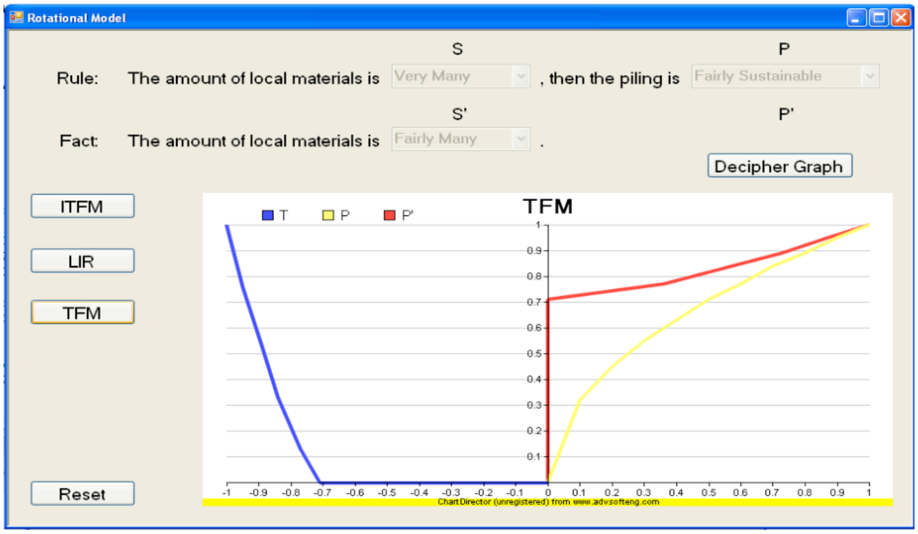


Figure A.18: Rotational Model – TFM Graph - Example 1

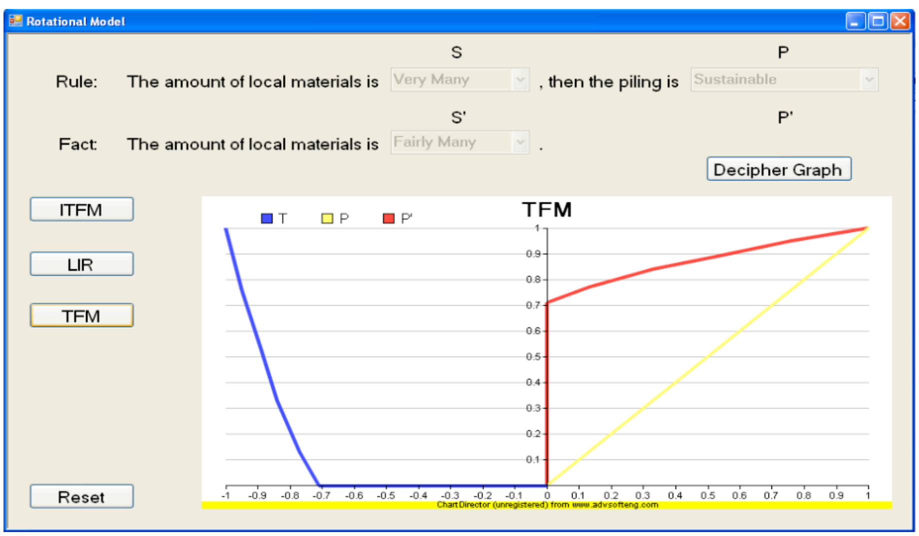


Figure A.19: Rotational Model – TFM Graph -Example 2

Angular Model:

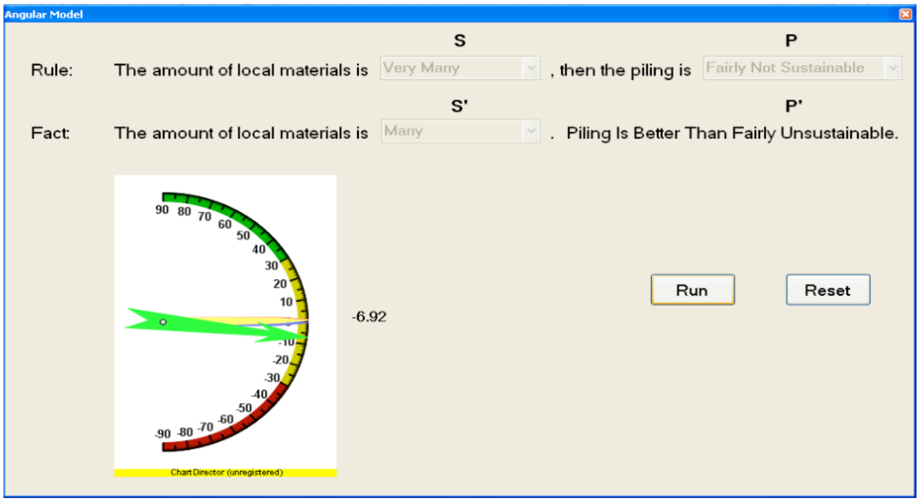


Figure A.20: Angular Model Example 1

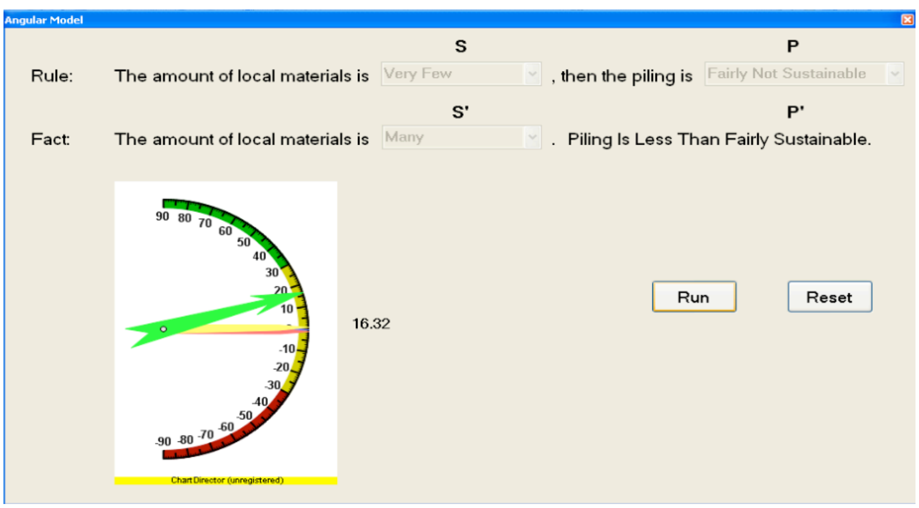


Figure A.21: Angular Model Example 2