Sustainable Bridges: Green Links to the Future

Thesis

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Abstract

Sustainable practices are a key component to almost every aspect of our lives. “Going Green” is incorporated into everything from food to buildings to cars. The civil engineering community is also responsible for becoming more sustainable in its practices, and this should include the bridges that are built.

There have been many advances in bridge technology over the last hundred years, but sustainable bridge design is still a new and different area of focus. There have been minimal attempts to make bridges more sustainable through material improvements and design enhancements, but to be holistically sustainable in terms of the environment, the people and the economics, further advancements are still needed.

During this research, programs were created based on fuzzy logic to help users assess the overall sustainability of a bridge design. The bridges at the focus of this research were new or major rehabilitation (reconstruction) bridge projects that cross a waterway with one or two lanes of traffic in either direction located in Columbus, Ohio. In total five programs were created for assessment, each based on a unique fuzzy logic model. The programs require different inputs from a user versed in sustainable bridge design practices who is mildly familiar with fuzzy logic principles. All five of the programs produce an output relating to a general sustainability rating so they can be compared and contrasted to determine the most appropriate model.
Further enhancements to the programs are needed to greatly influence the sustainable bridge community as a whole, but at this given time, the Mamdani Approach Model created is the best fit for determining the sustainability rating of a bridge project. The Mamdani Approach Model assesses the materials used in the project and the location of the project to determine a general sustainability rating. To further enhance this program along with the other programs created, it is recommended that the scope of the programs be expanded to other regions outside of Columbus, Ohio. Specific membership functions also need to be developed for application in the models, and additional variables could be added to the Mamdani Approach Model for enriched results. Another future recommendation would be to see how this research could be effectively incorporated in Greenroads. These enhancements will further develop the ideals of sustainable bridge design and will help demonstrate that sustainable designs are possible.
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Table of Contents

Abstract ........................................................................................................................................ ii
Acknowledgments .................................................................................................................. iii
Vita ............................................................................................................................................... iv
Table of Contents .................................................................................................................. v
List of Tables .......................................................................................................................... ix
List of Figures .......................................................................................................................... x
Chapter 1: Introduction ............................................................................................................. 1
  1.1 Introduction .................................................................................................................... 1
  1.2 Goal/Objective/Tasks ..................................................................................................... 2
  1.3 Background ................................................................................................................... 5
  1.4 Significance .................................................................................................................... 12
  1.5 Advantage ..................................................................................................................... 12
  1.6 Scope and Limitations ................................................................................................. 13
Chapter 2: Literature Search ..................................................................................................... 14
  2.1 Introduction ................................................................................................................... 14
  2.3 Current Green Bridge Rating Systems ......................................................................... 16
  2.4 Sustainable Bridge Programs, Initiatives and Affiliates ................................................ 17
    2.4.1 Sustainable Bridges ............................................................................................... 18
    2.4.2 Sustainable Bridge Design – APWA Conference .................................................. 19
  2.5 Inhabitable Bridges ....................................................................................................... 21
2.5.1 London Bridge ............................................................... 21
2.5.2 Ponte Vecchio ............................................................... 22
2.5.3 I-670 Cap ................................................................. 24

2.6 Conclusion ............................................................................. 25

Chapter 3: Sustainable Bridge, User and Fuzzy Logic Parameters .......... 27

3.1 Introduction ........................................................................... 27
3.2 Bridge Specifics ...................................................................... 27
3.3 User Specifics ........................................................................ 27
3.4 Conclusion .............................................................................. 29

Chapter 4: Fuzzy Logic ................................................................ 30

4.1 General Overview ................................................................. 30
4.2 Triangular Model ................................................................... 33

4.2.1 Introduction to the Triangular Model ................................. 34
4.2.2 General Overview of Theory Relating to the Triangular Model .... 34
4.2.3 How to Use the Triangular Model Program ....................... 35
4.2.4 Conclusion of the Triangular Model Program ....................... 38

4.3 Fuzzy Relation and Composition Model .................................... 39

4.3.1 Introduction to the Fuzzy Relation and Composition Model........ 39
4.3.2 General Overview of the Theory Relating to Fuzzy Relation and
Composition .................................................................................. 40
4.3.3 The Sample Relations ........................................................ 41
4.3.4 How to Use the Fuzzy Relation and Composition Model Program 43
Chapter 6: Summary/Conclusions/Recommendations ........................................... 71

6.1 Summary ........................................................................................................ 71

6.2 Conclusions ...................................................................................................... 72

6.3 Recommendations .......................................................................................... 73

References............................................................................................................... 77

Appendix A: Triangular Model Program Images .................................................. 80

Appendix B: Fuzzy Relation and Composition Model Program Images ............. 82

Appendix C: Mamdani Approach Model Program Images .................................. 84

Appendix D: Rotational Model Program Images .................................................. 86

Appendix E: Angular Model Program Images ...................................................... 90
List of Tables

Table 1: Linguistic Variables and Functions ................................................................. 40

Table 2: Feasibility and Cost Relations ........................................................................ 41

Table 3: Feasibility and Sustainability of Materials Relations .................................... 42

Table 4: Mamdani Inference Rules .............................................................................. 47
List of Figures

Figure 1: Sustainability ................................................................. 3
Figure 2: Eco-Bridge Chicago .......................................................... 6
Figure 3: Bamboo Pole ................................................................. 8
Figure 4: Bamboo Bridge at the technical University in Pereira .......... 9
Figure 5: Covered Bamboo Bridge ............................................... 9
Figure 6: Bamboo Bridge Beams ................................................... 10
Figure 7: Bamboo Beam Bridge with Load ................................... 11
Figure 8: Engineer's Influence and Potential Sustainable Improvement .... 20
Figure 9: Ponte Vecchio 2009 ....................................................... 23
Figure 10: Google Image of I-670 Cap ............................................. 24
Figure 11: Program Welcome Window .......................................... 32
Figure 12: Program Glossary ......................................................... 33
Figure 13: Triangular Model Program Opening Window .................. 35
Figure 14: Triangular Model Input Screen ..................................... 36
Figure 15: Expert Input Graph ...................................................... 37
Figure 16: Final Results of Triangular Model ................................. 38
Figure 17: Opening Window for Fuzzy Relation and Composition Model Program .... 43
Figure 18: Sample Input for Example ............................................ 44
Figure 19: Fuzzy Relation Graph for Example ................................. 45
Figure 20: Opening Window for the Mamdani Approach Model Program ..... 48
Figure 21: Example Output and Graph for Mamdani Example .......................................................... 49
Figure 22: Baldwin’s Truth Values ........................................................................................................ 53
Figure 23: Opening Window for Rotational Model Program .................................................................. 54
Figure 24: ITFM Graph .......................................................................................................................... 56
Figure 25: LIR Graph .............................................................................................................................. 57
Figure 26: LIR Graph .............................................................................................................................. 58
Figure 27: Baldwin Model Key in Program Model .................................................................................. 59
Figure 28: Opening Window to Angular Model Program ....................................................................... 62
Figure 29: Angular Model ....................................................................................................................... 63
Figure 30: Triangular Input 1 .................................................................................................................. 80
Figure 31: Triangular Output General 1 .................................................................................................. 80
Figure 32: Triangular Output Final 1 ...................................................................................................... 80
Figure 33: Triangular Input 2 .................................................................................................................. 81
Figure 34: Triangular Output General 2 .................................................................................................. 81
Figure 35: Triangular Output Final 2 ...................................................................................................... 81
Figure 36: Fuzzy Relation and Composition Input 1 ............................................................................... 82
Figure 37: Fuzzy Relation and Composition Output 1 ............................................................................ 82
Figure 38: Fuzzy Relation and Composition Input 2 ............................................................................... 83
Figure 39: Fuzzy Relation and Composition Output 2 ............................................................................ 83
Figure 40: Mamdani Sample 1 ............................................................................................................... 84
Figure 41: Mamdani Sample 2 ............................................................................................................... 85
Figure 42: Mamdani Sample 3 ............................................................................................................... 85
Figure 43: Rotational Model ITFM 1 ....................................................................................................... 86
Figure 44: Rotational Model LIR 1 ................................................................. 87
Figure 45: Rotational Model TFM 1 ................................................................. 87
Figure 46: Rotational Model ITFM 2 ................................................................. 88
Figure 47: Rotational Model LIR 2 ................................................................. 88
Figure 48: Rotational Model TFM 2 ................................................................. 89
Figure 49: Angular Model Sample 1 ................................................................. 90
Figure 50: Angular Model Sample 2 ................................................................. 91
Figure 51: Angular Model Sample 3 ................................................................. 91
Chapter 1: Introduction

1.1 Introduction

"Go Green!" This statement is one that has been heard in almost every aspect of our lives within the past few years. It relates to sustainable lifestyles and to a mindset that must be adopted by everyone for true success. As the world continues to develop its definition of sustainability, each engineering discipline has tried to focus its efforts to improve the quality of life while maintaining and improving, if possible, the environment and other areas of social interest. The civil engineering community is not exempt from "going green." Civil engineers are responsible for bettering the lives of the public through infrastructure. They are responsible for accomplishing this in an efficient and cost-effective way, and now it must also be done in a sustainable or "green" manner.

The research presented in this report details the use of multiple computer programs, which ultimately assist the user in determining whether or not a bridge is classified as sustainable. Many of the bridges in the U.S. will need to be rehabilitated or replaced in the up and coming years. According to MSNBC (2007), “As of 2005, 155,144 of the nation’s 592,473 bridges -- or 26.2 percent -- were rated structurally deficient or functionally obsolete.” Focusing on this topic should be of the utmost importance in helping to fuel a desire to incorporate the sustainable world into bridge development and construction.
Minor steps toward sustainable bridge design have been taken by various groups within the bridge design community. These advances range from using traditional materials in new ways to enhancing materials through innovative manufacturing techniques to creating programs aimed at increasing the longevity of a bridge design. While all of these items help to increase the possibility of building sustainable bridges, a way of assessing these bridges is still under development. The programs created in this research help to fill that gap in the bridge industry.

Each computer program created focuses on a different area of theory relating to fuzzy logic that helps to determine the sustainability of a bridge design. While the theories may differ greatly, the end result or output of each program was designed to be similar. A comparison of the outputs was conducted which draws upon the advantages and disadvantages of each approach. By creating these programs and comparing their results, a better understanding of the possibilities in relation to sustainable bridge design was achieved.

1.2 Goal/Objective/Tasks
Currently, there are programs available to help engineers determine whether or not a traditional building project is classified as sustainable. Sustainability in its most simple sense refers to longevity, but in the context of this paper sustainability means so much more. Sustainability for the purposes on this research refers to the “three e’s.” According to S.M. Wheeler and T. Beatley (2009) in The Sustainable Urban Development Reader those “e’s” are environment, equity, and economy. Put in another way, sustainability
could be thought of as planet, people, and profit as proposed by Shell Oil Company (2001) and Peter Frisk (2010), whose approaches are more business sector oriented. The concept of sustainability that fueled this research can be graphically represented by Figure 1. True sustainability is only achieved in the small intersection between the three parts.

![Figure 1: Sustainability](image)

To achieve sustainability for buildings, construction engineers often turn to the Leadership in Energy and Environmental Design (LEED) standard (United States Green Building Council [USGBC], 2010) as a basis for implementation. When speaking of bridge construction projects, no such nationally recognized rating system currently exists.

The goal of this research was to create a greater appreciation for sustainable bridge construction and to provide the civil engineering community with a framework of ideals to help them determine whether or not a bridge project is sustainable. By providing this
knowledge set and idea of possibilities, hopefully sustainable bridge construction will become a focus of concern for bridge engineers and designers.

To achieve this goal and based on the recent emergence of this area of interest, computer programs were designed that can be customized for use by an expert to assess the sustainability of a bridge project. An expert in the context of this research was someone who both possessed knowledge of sustainability, bridge design, and construction implementation. For some programs the user also needed to be familiar with fuzzy logic to interpret the final program output. The objective of this research was that those who work directly in the field of bridge construction would be able to utilize these programs to aid them in their future endeavors.

There were 3 specific tasks associated with these the achievement of the goals. They included:

1.) Gaining knowledge of sustainability and how that can be applied to bridges
2.) Researching current bridge practices as they relate to sustainability
3.) Developing fuzzy logic driven computer programs to aid in the assessment of sustainable bridge designs.

To achieve any of the overall goals relating to this research all of these tasks had to be completed in full.
1.3 Background

This study was developed after obtaining information about the up and coming Eco-Bridge to be built in Chicago. The Eco-Bridge shifted the direction of the research to gaining knowledge about sustainable building materials, mainly bamboo. Both of these topics helped to steer the overall scope of the programs and the study to enhance the systems that were created to help determine the sustainability of a bridge design.

The Eco-Bridge in Chicago will be a marvel in the sustainable construction industry once it is complete. It will bring together improvements in the quality of life and preservation of the environment. It will be a demonstration that enhancements to the quality of life do not need to be at the cost of the environment or at the cost of future generations’ environment. The following picture in Figure 2 is a rendering of what the Eco-Bridge will look like as proposed by Adrian Smith and Gordon Gill (2007), the design architects on the project, of ©Adrian Smith + Gordon Gill Architecture.
According to Blair Kamin (2008) in "Smith and Gill's 'eco-bridge': Coming to Chicago's lakefront,” the bridge will be approximately 2 miles long and will be located next to the current Navy Pier in Monroe Harbor, Chicago. Kamin (2008) continues to explain that it will be built as a breakwater and will provide an area for recreation while serving as an attraction for the city of Chicago. The bridge will be equipped with vertical wind turbines that will help to provide a source of energy for the city, and it will have a central observation tower as depicted in the Figure 2 rendering that will overlook both the water and Chicago skyline. The bridge itself will be made from a base of slag, a byproduct of steel production. The base will be permeable which will serve as a habitat for wildlife in Lake Michigan. While these are only some of the many details of the project, it can be seen that this will be a sustainable project unlike any other that encompasses
improvements in human life while helping to sustain, and even in some cases, enhance the surrounding environment.

Sustainable building materials are everywhere and have been used in construction for many years. Their uses have been mainly specialized until now, but as society moves to a “greener” view, their applications and versatility have increased drastically. In addition to the advances already made, their functional uses should continue to multiply and spread over time with improved sustainability awareness and with further enhancements to technology. One area for expansion is the use of these materials in green bridges. Sustainable materials have become more common in the construction of buildings, but using these materials for bridge construction has been minimal. Through the course of this study many materials that can be categorized as sustainable were examined, but bamboo will be the focus of this report because of its abundance and overall versatility.

Bamboo is a naturally occurring sustainable material, which is ideal for green construction for many reasons. It grows similarly to grass so it is a construction material that is readily available. This makes it easy to harvest with minimal destruction to the environment. It has many physical characteristics that make it ideal for finishing aspects of building projects. Figure 3 below shows the internal structure of a bamboo pole. Note the cylindrical shape that helps to give it naturally high strength.
Figure 3: Bamboo Pole (Stamm, 2009)

One of bamboo’s more common uses is as a decorative material such as floor coverings, but recently it has also been used as a main building material for the support system of major structures. Mason Inman (2007) states in "Bamboo Road Bridge Can Support 16-tonne Trucks" that bamboo is stronger than steel in tension and stronger than concrete when compared pound per pound. This fact makes the material ideal for multiple uses.

An extraordinary example of how bamboo can be used in a bridge in a unique and different way is showcased in the work done by Jörg Stamm at Eco Bamboo (Henrikson, 2008). Stamm does work in many different areas of construction including home construction, but the work he showcases on bamboo bridges demonstrates that sustainable bridge design is indeed possible. Figure 4 and Figure 5 are two examples of
the possibilities available when using traditional bamboo to construct a very nontraditional pedestrian bridge.

Figure 4: Bamboo Bridge at the technical University in Pereira (Stamm, 2009)

Figure 5: Covered Bamboo Bridge (Stamm, 2009)
As the interest in green building has continued to develop, new technologies have emerged which demonstrate that green materials can be used not only in new and unique ways, but they can be engineered for increased applications. The use of bamboo in bridge design is no exception. Professor Yan Xiao at the University of Southern California along with his colleagues has developed a new way of using bamboo as a material in the construction of vehicular designed bridges (Xiao, Shan, Chen, Zhou, & She, 2008). The bamboo that is used in these bridges is cut into planks and then glued together to form a very strong composite bamboo material (Inman, 2007). The product is a type of glulam, which the researchers refer to as GluBam® (Xiao et al, 2008). This new bamboo product is still being improved and tested, but Figures 6 and 7 show its first real world application in a bridge in the Daozi Village in Leiyang, Hunan Province, China (Xiao et al, 2008).

Figure 6: Bamboo Bridge Beams (Xiao, Zhou, & Shan, 2009)
This GluBam® bridge can hold up to a 16 ton truck and was constructed in a week with only eight workers (Inman, 2007). As products similar to this continue to be developed the possibilities of what can be accomplished through green engineering and sustainable bridge design are endless.

These topics greatly influenced the scope of the programs developed during the course of this research. The programs use different principles to establish the sustainability of a bridge, but they all centered on the idea that sustainable bridges are vital to the future and that they are possible with proper planning and thoughtful preparation. The background
information gathered was not specifically showcased in the programs, but it did play an integral part in their general development.

1.4 Significance
The significance of this research was quite evident in today's society. Being sustainable is becoming a standard in every area of life. Sustainable crops, sustainable buildings, sustainable materials, and sustainable cars are at the forefront of this movement. The design and construction of infrastructure, especially bridges in the case of this research, should be no different. The design and construction of bridges must be explored in a sustainable way. Right now this is simply a vision of what could be, but there is no doubt that sustainable ideas, concepts, and practices will become the standard of life and bridge design and construction.

1.5 Advantage
The advantage of this research was that it will serve as a stepping-stone into the possibilities of sustainable bridge design. The programs developed for this research refer to a wide array of bridge topics and areas of implementation. This allows the programs to be used in a wide range of circumstances. The programs were developed in such a way that the details can be customized to the expert's specifications and needs. This allowed them to be more universal and useable to the public in the future.
1.6 Scope and Limitations

The programs created to help in the calculation of the sustainability of a bridge have a narrow scope at this time. These programs were developed for one to two lane bridges (one to two lanes in either direction) over waterways in Columbus, Ohio. The bridges to be evaluated must be in the planning stages, which have yet to begin the construction phase or they may be major rehabilitation (reconstruction) projects. Bridges that are currently in use cannot be evaluated by these programs because no changes can be made and possibly detailed facts about their past such as the processes used for their construction are most likely unknown. The current scope of these programs is limited, but the scope could be expanded in the future to encompass different types of bridges in a multitude of locations. Many of the details in these programs are purposely broad so that the expansions can be possible. The details are also intentionally open-ended because the true definition of a sustainable bridge has yet to be defined by the bridge industry.

Another limitation to the research has to do with the fuzzy logic based programs. These programs rely on the use of membership functions. The creation of an ideal membership function takes much research and preparation. This is out of the scope of this report. The membership functions used model possible membership functions, but in no way were these functions chosen to be perfect models for the circumstances. With fuzzy logic, the ideal membership function will serve to provide more accurate results but not more accurate enough to be an area of concern for this research. The general trends and results achieved by these programs follow closely with the presumed outcomes of specialized membership functions.
Chapter 2: Literature Search

2.1 Introduction

A minimal amount of research has been completed to date that specifically relates to the sustainability rating for bridge designs. The ideas and concepts behind incorporating sustainability into a bridge design mirror those of programs in place for buildings, so the notion of using these philosophies and outlooks when examining bridges is not unrealistic. The theories and programs available for sustainable buildings simply need to be modified to be applicable for bridge design or at least serve as inspiration for a unique rating system.

To better understand how a sustainability rating can be given to a bridge design, one must first understand current general sustainability initiatives and practices and must understand past work on bridge ratings. Finally one must be familiar with bridges that have already been constructed that embody sustainable attributes even if the bridges were not specifically intended to demonstrate these characteristics and if they do not fit perfectly into the scope of this research. These ideas served as the basis for the literature search that was conducted.
2.2 LEED Ratings for Buildings

Leadership in Environmental and Energy Efficient Design (LEED) which was developed by the United States Green Building Council (USGBC) focuses on green and sustainable buildings both commercial and residential (2010). Under LEED version 3, the rating systems takes into account factors related to 9 main categories which are:

- Sustainable Sites
- Water Efficiency
- Energy & Atmosphere
- Materials & Resources
- Indoor Environmental Air Quality
- Locations & Linkages
- Awareness & Education
- Innovation in Design
- Regional Priority

These categories are evaluated on a points system where there are a total of 110 points possible. The system breaks these general categories down into more specific topics. The 110 points are then allocated to the specific topics. The allocation is slightly different depending on the type of building project. Once the points have been distributed, the building may receive one of 4 LEED ratings. The ratings are:

- Certified (40–49 points)
- Silver (50–59 points)
- Gold (60–79 points)
- Platinum (80+ points)
In terms of sustainability as it has been defined for this research focusing of the ideals of people, planet and profit, LEED loosely focuses on people and profit, but most of LEED’s emphasis is on the environmental component of sustainability. Using LEED as a base for a sustainable bridge rating system, this research hoped to provide a more holistic sustainability approach to evaluating a sustainable bridge that considers the environment, the people and profit more equally than LEED currently does.

2.3 Current Green Bridge Rating Systems

While there is no official sustainability rating system for bridge designs, some research was done by Lauren R. Hunt (2005) at MIT which began to examine the possibility of a rating system for sustainable bridges. In the document titled “Development of a Rating System for Sustainable Bridges,” a system was developed based on LEED version 2.1 that focused on five main categories (Hunt, 2005). Those categories were:

- Sustainable Sites
- Traffic Efficiency and Alternative Transportation
- Water and Energy Efficiency
- Materials and Resources
- Innovation and Design

Within the five categories there were 18 different criteria and a total of 25 points available for a bridge design. The criteria ranged from erosion and sedimentation control to footing and pier location to life cycle assessment.
Hunt (2005) focused on three different bridges, the Leonard P. Zakim Bridge in Boston, MA, the Arthur J. Ravenel, Jr. Bridge in Charleston, SC and the Potomac River Bridge crossing from MD to VA, for the rating system. Based on the criteria and the established rating system, the Potomac River Bridge would have received the highest rating which would have been between 10 and 13 points (there is a range of points because some of the details about the project were unknown). For a bridge to achieve the a sustainability rating a minimum of 10 points out of the possible 25 is required. During the evaluation the Zakim Bridge received 6-10 points and the Ravenel Bridge received 8-11 points.

The system created during Hunt’s research lead the direction of the programs created in this research to be more flexible in their assessment of what is sustainable. This general concern directed the research towards using fuzzy logic when determining the sustainability of a bridge design. Also as shown by Hunt’s work, when evaluating existing bridges, many of the factors relating to its construction are unknown and therefore cannot be properly accounted for in the rating system. This fueled the scope of the programs in this work to focus only on planned projects including both new and major rehabilitation bridges.

2.4 Sustainable Bridge Programs, Initiatives and Affiliates

The following programs and reports discuss information loosely related to the specific items of this research but they do relate to the general goals as described in Section 1.2. The details about each project are different from the details of this research, but each item
presented below helps to expand the knowledge base of materials relating to sustainable bridge design.

2.4.1 Sustainable Bridges

The European Commission within the 6th Framework Programme has developed a project called Sustainable Bridges – Assessment for Future Traffic Demands and Longer Lives (2008). The sustainable definition for this group is more focused on longevity rather than the three topic approach taken for this research. The Sustainable Bridge program targets the enhancement of railway bridges in Europe. Their three main goals are to:

1. Increase the transport capacity
2. Extend the residual service life
3. Enhance management, strengthening and repair systems

These concentrations of interest are very different from the categories previously outlined in both LEED and the sustainable bridge rating system, but the underlying theme of specifically improving bridges to help enhance a sustainability driven mindset through infrastructure improvements is fundamentally similar. The details of this program do not align directly with the concerns of this work, but the program does provide a view into what others are currently doing to enhance bridge designs sustainably. Another added benefit of this program is that it demonstrates a global concern for sustainable bridge infrastructure.
2.4.2 Sustainable Bridge Design – APWA Conference

At an American Public Works Association (APWA) conference, a presentation was given by Kelly Burnell (2009) titled “Sustainable Bridge Design.” The focus of the presentation was on the bridge engineer’s impact on a bridge project over its lifespan which helps to demonstrate when engineers have the most influence on the sustainability of a bridge. They examined the life of the bridge to be made up of six components. Those components are:

- transportation system
- determining the bridge function
- design
- construction
- operation
- maintenance
- rehabilitation-demolition-replacement

The potential for sustainable improvements according to Burnell (2009) is the highest in the first stage and decreases exponentially through the other phases before it briefly begins to rise again during the rehabilitation-demolition-replacement. The other element of interest during this presentation was the bridge engineer’s influence during the project life. This variable in the project started off very low in stage one, transportation system, and peaked during the design phase. Right after construction, the influence of the bridge engineer began to slowly rise again to about half of the peak influence during the final stage. Figure 8 depicts a graphic that demonstrates the bridge engineer’s influence and the overall potential for sustainable improvements in the project.
Based on Burnell’s (2009) findings the bridge engineer has the most influence during the design phase which still allows for sustainable improvements to be made. This region is therefore suggested as the area of focus for engineers wanting to improve the sustainability of a bridge project. This information helped to solidify the notion that this research would be for planned and major rehabilitation bridge projects only, as did the work by Hunt (2005). At this stage of the project, the engineer has the most control and therefore can have the most impact available to them over the span of the bridge’s life.
The rest of the presentation discusses specific designs and materials that can be used to be more sustainable in terms of lowering the energy input in the bridge, increasing the durability and simplifying the deconstruction. While these are important factors to consider, they are beyond the scope of this research.

2.5 Inhabitable Bridges

In terms of a holistic sustainability plan, inhabitable bridges were found to meet many of the objectives more so than traditional vehicular-only bridges. It should be noted that these bridges are not the focus of this research, but they do provide an interesting view of the possible future of sustainable bridge design by looking into bridges that have already been an integral part of society. These bridges can serve as visions of the past, present and future.

2.5.1 London Bridge

The segmented arch London Bridge that is often pictured today is not the original inhabited bridge that existed in London years ago. Murray and Stevens (1996) state in their book *Living Bridges: The Inhabited Bridges, Past, Present and Future* that the original London Bridge, called the Old London Bridge, was an inhabitable bridge that spanned the Thames for over 600 years. The authors continue to explain that the stone version of the bridge built between 1176 and 1209 not only served as the main link across the Thames, but it was also a center for urban development and centralized expansion. It was approximately 285 meters long, 4.6 meters wide and 18.5 meters high. Many fires
plagued the bridge, but it was constantly rebuilt serving as a base for homes, churches and businesses.

In a simple sense of the term, the development of the bridge can be seen as sustainable in nature. It was a highly dense location with mixed use buildings providing an economical and equitable support center to London. The environmental impacts of the bridge are difficult to define, but even hundreds of years ago, two of the three main aspects of sustainability were being met to a full capacity. The inhabitable iteration of the bridge was demolished in 1823 (Murray and Stevens 1996).

2.5.2 Ponte Vecchio

Ponte Vecchio or “Old Bridge” is located in Florence, Italy and continues to serve a similar function as the London Bridge did many years ago. Brown (2005) states in his book Bridges: Three Thousand Years of Defying Nature that Ponte Vecchio spans the Arno with a length around 85 meters. Brown (2005) continues to describe that the bridge known today is actually a newer version of the original timber bridge that used to span the river. Construction on the new Ponte Vecchio began in 1345. Similar to the London Bridge, Ponte Vecchio is lined with both shops and housing and has been considered a “continuation of the city’s living and commercial space, rather than simply a link across the Arno” (Brown, 2005, p. 32). It is not just a means to get over the river. It is a living component to the city. A current day image of the Ponte Vecchio can be seen below in Figure 9.
Over time, the Ponte Vecchio has changed slightly. For example, originally the main businesses populating the bridge were butcher shops, but from 1593 forward, the shops were mainly owned by jewelers and goldsmiths (Murray and Stevens 1996). Other than the retail focus change, the bridge still serves a similar purpose to the one set out for it during its conception. Like the London Bridge, Ponte Vecchio is not truly sustainable in terms of the environment, the people, and the economics, but it does provide a vision for how bridge design can be changed to be more than simply a way to move from one side of a city to another.
2.5.3 I-670 Cap

The I-670 Cap in Columbus, Ohio can be considered a modern day version of an inhabitable bridge. The I-670 Cap is a segment of High Street that spans over interstate 670 connecting The Short North to the area just north of the Arena District in downtown Columbus. Below in Figure 10 is a satellite image from Google Maps (2010) of the I-670 Cap with labels added to clarify the location.

![Google Image of I-670 Cap](image)

Figure 10: Google Image of I-670 Cap

On the cap are a multitude of restaurants and at one time shops that make the flow over the interstate seamless. Mayor Michael Coleman was quoted as writing “This downtown
development project should be a model for other cities searching to reconnect the urban fabric that was cut by the construction of freeways” (Federal Highway Administration, 2005). Unlike the London Bridge and Ponte Vecchio, the I-670 Cap does not have urban living spaces, but it is an example of how an old idea can be applied today with modern construction methods and materials. Like the other two bridges, it is difficult to say that this project is sustainable as defined in this research, but it does open the door for the possibilities available in terms of functional yet sustainable infrastructure.

2.6 Conclusion
The literature search conducted on sustainable bridge design yielded interesting and mixed results. The research shows that there are currently efforts in the works for creating or at least promoting the idea of sustainable bridge designs. Unfortunately, the current rating systems available do not meet the needs of truly being able to determine the sustainability of a bridge. The current rating systems are either only focused on buildings and do not account for the nuances of a bridge project or are too specific given the current state of sustainable bridge design. There is hope, however, for the future of sustainable bridges.

There are programs in place and discussions being held that promote the ideas of sustainable bridges. The details of these programs are still in the development stages and take on a wide array of ideas and topics so a method to assess the sustainability of a project must take into account the underdeveloped nature of the field. Also there are current examples of bridges that have defied the norm to showcase what sustainability
can mean on a completely different and unique level. The research presented here suggests that a way to determine the sustainability of a bridge with many unknowns and variables is through the use of fuzzy logic models.
Chapter 3: Sustainable Bridge, User and Fuzzy Logic Parameters

3.1 Introduction

To help identify the uses of the programs created for this research, the specific details about the bridge being evaluated had to be defined along with the specific requirements of knowledge needed by the user. If these details are not met by the project or by the user, the programs will not be able to provide useful or meaningful results. In the future these parameters may be widened to be more flexible, but at this time, they must be met for success while implementing the programs.

3.2 Bridge Specifics

As stated in the scope and limitations section of this document, the programs created for this research were to be used for new and major rehabilitation (reconstruction) bridge projects in Columbus, Ohio. The bridges to be evaluated by the programs are two or four lane vehicular bridges (one or two lanes in each direction) that traverse a waterway. Once the user has identified the bridge project, he/she then begins to use the programs to help determine sustainable aspects of the design.

3.3 User Specifics

The programs were created to help determine sustainable principles of bridges and therefore must be used by an expert who is very familiar with sustainability and the details about the bridge itself. Since the programs are all based on fuzzy logic principles,
many of the inputs into the programs are broad and require the knowledge of an expert. While the expert must be knowledgeable in sustainability and bridge construction, he/she does not necessarily need to be an expert in fuzzy logic. The expert should understand the basic principles of the methodology, but they do not have to understand the underlying workings of every model. They should be able to receive the output and apply it to their project accordingly.

In terms of sustainability, the expert should be familiar with all three aspects of sustainability (people, planet, and profit). They should understand how these three components work together to form a sustainable component in society. While it is not required to be able to use the programs, it would be beneficial if the user had some knowledge about LEED. LEED is used to determine green ratings on buildings only, but since there is no such standardized mechanism in place to determine the sustainability of a bridge at this time, familiarity with this system may help to put the sustainability of the bridge design in context for the user.

For fuzzy logic, the user of the programs should understand the basic principles that are presented throughout this paper. Fuzzy logic takes linguistic terms then manipulates, aggregates, and analyzes them to arrive at a final result, which is also linguistic in nature. The manipulation of the inputs is done using many mathematical principles, but each model focuses on using different avenues of alteration, which makes each program unique in its inputs and results. This can make direct comparisons of each model
problematic, but the overall arching themes and results of the models can be compared and analyzed.

3.4 Conclusion
As stated previously, these programs could be used to determine sustainable principles of many new bridge designs or rehabilitation (reconstruction) projects. The focus of the projects should be two or four lane vehicular bridges that cross a waterway in Columbus, Ohio, but for the purpose of demonstrating and analyzing these programs, general sample cases have been shown for each program. For purposes of continuity, similar cases have been examined for each model to help showcase their likenesses.
Chapter 4: Fuzzy Logic

4.1 General Overview

Fuzzy logic is a way to give meaning to a linguistic term that is often subjective in nature. Many times terms such as "almost true" or "fairly false" are used to describe the state of something. This can be problematic because it is very difficult to determine what these terms actually mean. Is "almost true" true? Is it false? One cannot say for certain which is correct. Using fuzzy logic allows for these terms to be quantified and manipulated determining a fuzzy level or linguistic interpretation of whatever is being measured.

There are many different approaches to using fuzzy logic. The following approaches or models were covered in this research:

- Triangular Model
- Fuzzy Relation and Composition Model
- Mamdani Approach Model
- Rotational Model
- Angular Model

Each approach uses different logic and reasoning, but they all focus on the fundamental concept of changing a linguistic term to a quantitative value back into a linguistic or fuzzy result that can be applied to the sustainability rating of a bridge design.
Using fuzzy logic for this research was essential because of the bias associated with how one may deem something to be sustainable. The word sustainable has been defined in this research to mean a state where a balance is achieved between people, planet and profit (Fisk, 2010 & Shell Companies, 2001). This helps narrow the definition, but it still leaves room for interpretation. This is why fuzzy logic principles and manipulations were vital for this research. They allow the user to interpret the variables on a linguistic scale which accounts for a portion of the uncertainty with defining sustainability for bridges. Also the adequate level of sustainability for one person or one community may be different depending on their development, location and knowledge. Allowing these groups to use fuzzy terms instead of rigid numbers allows for a more fluid approach to the analysis that provides a linguistic answer which can then be interpreted based on need.

As stated previously, five programs were created for this research each based on a different fuzzy logic model. All of the model programs are combined together into one program for easy access by the user. The main page of the program is depicted below in Figure 11.
This program is designed to help users identify the sustainability of a planned bridge design using fuzzy logic models. Sustainability in the context of this program focuses on people, planet, and profit. For true sustainability all three of these areas must be met in full capacity.

Choose one of the following models to determine whether or not a planned bridge design is sustainable. You may also choose to view the glossary for definitions to commonly used words in the various programs.

Figure 11: Program Welcome Window

From this window all five program models may be accessed by the user. Also a glossary of terms can be accessed from the main window page. Figure 12 depicts the glossary created for the program.
Each model is independent with unique inputs and individualized outputs, but for a full assessment, the programs can all be run individually for a single project and the user can compare their results. The results of running each program for a single bridge design will provide the user with a more general understanding and assessment of whether or not their bridge design is sustainable.

4.2 Triangular Model

The Triangular Model created for this research examines the experience of experts and their general sustainable rating of a bridge design. The model followed for the development of the program is outlined in “Fuzzy Set Concepts for Evaluating Performance of Constructed Facilities” written by Fabian C. Hadipriono (1988). This article outlines the mathematical approaches associated with using the Triangular Model.
for the assessment of any topic. The specific details of this model are not discussed at length in this report.

4.2.1 Introduction to the Triangular Model

A program was created to demonstrate the use of the Triangular Model in relation to sustainable bridge design assessment. This particular program requires the input of three experts. The program could be expanded to accommodate more expert opinions, but for the purposes of this research, only three experts were focused on. If the program were expanded to account for additional expert input, the principles underlying the evaluation would be unchanged. The goal of this program is to compare the ratings of the single bridge design while accommodating for the differences in experience level. The underlying results of this model show that experts with more experience have ratings that carry more weight in the analysis as compared to those who have less experience.

4.2.2 General Overview of Theory Relating to the Triangular Model

Using linguistic terminology to describe a project is a very common practice, but linguistic terms can be difficult to interpret and fully understand due to personal opinions and experiences that may alter the meaning of a linguistic evaluation from one person to another. To overcome this phenomenon, graphical representations of these linguistic terms can be generated that help quantify the inexact description. The Triangular Model used in this evaluation uses a users rating on a scale of 1 to 10, converts that to a graphical representation and then aggregates the graphs to arrive at a final linguistic
output that is defined. To arrive at this final result, a fuzzy average rule and fuzzy algebra are both used.

4.2.3 How to Use the Triangular Model Program

Once the user has selected the Triangular Model button from the starting window for the general program (see Figure 11), which showcases all the models, the user will input the experience in years of the three experts along with their sustainability rating. This data must be entered into the window depicted below in Figure 13.

![Triangular Model Program Opening Window](image)

Figure 13: Triangular Model Program Opening Window

For purposes of this research, the program has been set to allow the user to input experience level in a range of years. The user should follow the subsequent system for entering the experience level. If the expert has 4 years of experience, enter 4 to 4. If the expert has 6.5 years of experience, enter 6 to 7. If the user has 10 or more years of
experience, enter 10 to 10. This method of entry allows more flexibility in the inputs. The experience in years should be related to their experience working with sustainable bridge projects, not just bridges or sustainability issues.

After the user has entered the experience levels of the experts, they may now enter the rating the user gave the bridge in terms of sustainability on a 1 to 10 scale. The same convention for entering the rating should be followed that was used to input the experience level. For example, if the rating was a 2, the user should enter 2 to 2. If the rating was a 7.5, the user should enter 7 to 8. The user may also expand their ratings if necessary. For example, a rating of 5 to 7 may be selected. Once all the information has been entered the screen should look similar to the following window in Figure 14.

![Triangular Model Input Screen](image.png)

Figure 14: Triangular Model Input Screen
After all the data has been entered the user must select "Submit." Once Submit has been selected, two tabs will appear in the upper left hand corner of the window. The user may click on the second tab labeled "Expert Input" to see the two graphs generated by the model. The first graph is for the experience level of the three experts and the second graph is the sustainability levels given by the experts. The graphs for the sample data entered in Figure 14 can be seen in Figure 15.

These graphs display the experience levels of the three experts to the left in green and their rating of the bridge is displayed to the right in red. The program has taken the experience levels and ratings in simple numerical entries and has expanded them into lines or triangular shapes depending on the input. This allows the model to use the entries as a range if needed instead of a single data point.
The third tab, titled "Final Results," will show the composite of the information when selected. This graph has taken into account the inputs of the expert including experience level and rating to develop a final result. The model has manipulated the data in such a way to take the weighted average of the results giving more bearing to the ratings from experts with more experience compared to those experts with less years of experience.

The following final graph in Figure 16 shows the combined results of the sample input.

![Figure 16: Final Results of Triangular Model](image)

Based on the input data for the sample data the user would be able to determine that this bridge is better than fairly sustainable based on the three experts’ ratings.

4.2.4 Conclusion of the Triangular Model Program

The Triangular Model is a method that employs both expert assessment and experience to evaluate the sustainability rating of the bridge design. It uses fuzzy logic manipulations...
such as fuzzy averages and fuzzy algebra to produce a final result that is linguistic but defined on a graphical scale. This model is ideal for bridge projects where little detail is known about the specifics of the project, but a general assessment of the bridge can be made by experts who are versed in sustainability concepts as they relate to bridge design. Also for this model to truly be appropriate, different experts’ opinions are needed to generate an average result. As stated previously, this program has been developed to accept 3 ratings but it could be expanded to assess more inputs. See Appendix A: Triangular Model Program Images for additional images of results from this program.

4.3 Fuzzy Relation and Composition Model

The Fuzzy Relation and Composition program developed for sustainable bridge design is based on the computations demonstrated in “Assessment of Falsework Performance Using Fuzzy Set Concepts” by Fabian C. Hadipriono (1985). The membership functions used in this article were also used in this program as a basis for implementation. Creating a unique membership function is beyond the scope of this research. For more detailed information on the specifics of completing a Fuzzy Relation and Composition analysis please refer the Hadipriono (1985) article.

4.3.1 Introduction to the Fuzzy Relation and Composition Model

The program developed focuses on cost, feasibility and sustainability of a bridge project. All of these categories will be defined linguistically by the user in terms of specific topics. The specific topics were chosen based on similar requirements that are outlined for green building construction by LEED (USGBC, 2010). Based on the user input the
sustainability rating of the bridge design will be determined based on the cost and feasibility parameters relating to materials and location.

4.3.2 General Overview of the Theory Relating to Fuzzy Relation and Composition

The basis of this model is focused on matrix manipulations. Based on the user input a fuzzy set is assigned to the linguistic variable chosen by the user. Table 1 below shows the specific membership functions assigned to the different linguistic inputs available to the user in the program.

<table>
<thead>
<tr>
<th>Cost</th>
<th>Sustainability</th>
<th>Feasibility</th>
<th>Values ($f$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very Inexpensive</td>
<td>Very Sustainable</td>
<td>Very High</td>
<td>[0.36/0.8, 0.81/0.9, 1/1]</td>
</tr>
<tr>
<td>Inexpensive</td>
<td>Sustainable</td>
<td>High</td>
<td>[0.6/0.8, 0.9/0.9, 1/1]</td>
</tr>
<tr>
<td>Moderate</td>
<td>Moderately Sustainable</td>
<td>Medium</td>
<td>[0.6/0.3, 0.9/0.4, 1/0.5, 0.9/0.6, 0.6/0.7]</td>
</tr>
<tr>
<td>Expensive</td>
<td>Unsustainable</td>
<td>Low</td>
<td>[1/0, 0.9/0.1, 0.6/0.2]</td>
</tr>
<tr>
<td>Very Expensive</td>
<td>Very Unsustainable</td>
<td>Very Low</td>
<td>[1/0, 0.81/0.1, 0.36/0.2]</td>
</tr>
</tbody>
</table>

Table 1: Linguistic Variables and Functions

Once the sets have been assigned, the matrices are manipulated. First, the individual comparisons for each element are made to create a matrix of all the minimum values associated with that item in their assigned set. Second, all of the element matrices are combined together by taking the maximum values. Next, those matrices are manipulated by obtaining the maximum of all the minimum values. The final function values to be graphed are generated by simply taking the maximum in each column of the previous matrix. Once the function values are determined, those values are graphed to determine the sustainability result.
4.3.3 The Sample Relations

For this model to operate effectively, a set of relationships between the input variables had to be established. Two relations were examined. The first was between the cost and the feasibility of the bridge project location. In terms of location the following specific elements were considered:

L1 - Choosing a location to minimize environmental impact

L2 - Choosing a location that is not ideal for other construction

L3 - Choosing a location close to local building materials

For each of these items the level of feasibility and cost must be determined. The user has ultimate control over the relationships, but the following chart in Table 2 was developed as a base to be used if the user is unsure of the relationships within their specific bridge project.

<table>
<thead>
<tr>
<th>Feasibility of Choice</th>
<th>Cost of Location</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Very Inexpensive</td>
</tr>
<tr>
<td>Very High</td>
<td>L1</td>
</tr>
<tr>
<td>High</td>
<td>L1</td>
</tr>
<tr>
<td>Medium</td>
<td>L3</td>
</tr>
<tr>
<td>Low</td>
<td></td>
</tr>
<tr>
<td>Very Low</td>
<td></td>
</tr>
</tbody>
</table>

Table 2: Feasibility and Cost Relations
The second relationship was between the feasibility of the bridge design and the sustainability of the materials being used. In terms of materials the following specific elements were considered:

M1 - Establishing practices to minimize construction pollution
M2 - Using minimal construction resources
M3 - Reusing or recycling waste materials
M4 - Using recycled materials in the construction
M5 - Using non-recycled materials that use recycled materials

An example of an M4 material would be previously used steel beams in a major rehabilitation project. An example of an M5 material would be concrete that uses recycled concrete or fly ash in its mix design. For each of these items, the level of feasibility and the sustainability associated with it must be determined. As with the materials criteria, the user has ultimate control over the relationships, but the following chart in Table 3 was developed as a base to be used if the user is unsure of the relationships within their bridge project:

<table>
<thead>
<tr>
<th>Feasibility of Choice</th>
<th>Sustainability of Materials</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Very Unsustainable</td>
</tr>
<tr>
<td>Very High</td>
<td>M1</td>
</tr>
<tr>
<td>High</td>
<td>M5</td>
</tr>
<tr>
<td>Medium</td>
<td>M5</td>
</tr>
<tr>
<td>Low</td>
<td></td>
</tr>
<tr>
<td>Very Low</td>
<td></td>
</tr>
</tbody>
</table>

Table 3: Feasibility and Sustainability of Materials Relations
4.3.4 How to Use the Fuzzy Relation and Composition Model Program

When the user first begins using the Fuzzy Relation and Composition Model program they will see the following opening window depicted in Figure 17.

![Opening Window for Fuzzy Relation and Composition Model Program](image)

Figure 17: Opening Window for Fuzzy Relation and Composition Model Program

The user will need to enter the level of feasibility, cost and sustainability for each specific item. The example presented in Figure 18 follows the suggested relationships presented in Tables 2 and 3 above.
For each item choose the linguistic value that best corresponds to how the element relates to the bridge project. Once all the values have been determined, select Submit to process the data. To view the results, click on the Fuzzy Relation Graph tab when it appears.

<table>
<thead>
<tr>
<th>Location:</th>
<th>Feasibility of Location:</th>
<th>Cost of Location:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Choosing a location to minimize environmental impact:</td>
<td>Low</td>
<td>Very Inexpensive</td>
</tr>
<tr>
<td>Choosing a location that is not ideal for other construction:</td>
<td>Medium</td>
<td>Very Inexpensive</td>
</tr>
<tr>
<td>Choosing a location close to local building materials:</td>
<td>Medium</td>
<td>Very Inexpensive</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Materials:</th>
<th>Feasibility of Using Materials:</th>
<th>Sustainability of Materials Used:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Establishing practices to minimize construction pollution:</td>
<td>Very High</td>
<td>Moderately Sustainable</td>
</tr>
<tr>
<td>Using minimal construction resources:</td>
<td>Medium</td>
<td>View Sustainable</td>
</tr>
<tr>
<td>Reusing or recycling waste materials:</td>
<td>Very High</td>
<td>Sustainable</td>
</tr>
<tr>
<td>Using recycled materials in the construction:</td>
<td>Low</td>
<td>View Sustainable</td>
</tr>
<tr>
<td>Using non-recycled materials that use recycled materials:</td>
<td>High</td>
<td>Un Sustainable</td>
</tr>
</tbody>
</table>

![Fuzzy Relation and Composition](image)

Figure 18: Sample Input for Example

Once the user has entered in all the information, he/she must select “Submit” and then switch tabs to the “Fuzzy Relation Graph” tab to see the final output. The final graph for the example presented in Figure 18 is shown below in Figure 19.
Figure 19: Fuzzy Relation Graph for Example

Based on this graph the user would be able to determine the sustainability of the bridge. A graph that is predominantly skewed to the right is representative of a more sustainable bridge design than a graph skewed to the left. The exact interpretation of the results will be left up the user. Based on the suggested relationships in Tables 2 and 3, the results for this situation would create a better than fairly sustainable bridge project.

4.3.5 Conclusion of the Fuzzy Relation and Composition Model Program

The Fuzzy Relation and Composition Model is a detailed approach to determining the sustainability of a bridge design. It requires the input of multiple linguistic variables by the user that relate to specifics about the bridge project being studied. As it is currently developed, this program provides a more detailed assessment of the sustainability
compared to some of the other programs developed. See Appendix B: Fuzzy Relation and Composition Model Program Images for additional images of results from this program.

4.4 Mamdani Approach Model

The Mamdani Approach Model program developed for sustainable bridge designed is based on “Construction Project Delay Analysis Using Fuzzy Set” by H.M. Al-Humaidi and F. Hadipriono Tan (2008) in conjunction with “Application of Fuzzy Logic to Approximate Reasoning Using Linguistic Synthesis” by E.H. Mamdani (1976). These two articles demonstrate in great detail the workings of the Mamdani Approach and served as the basis for the implementation of this model in the developed program.

4.4.1 Introduction of the Mamdani Approach Model

The Mamdani Approach as used in this research compares two general ratings associated with a sustainable bridge design project. Based on these two ratings, graphical manipulations are performed to arrive at an overall sustainability assessment for the project. The nature of this program allows for a wide array of user input which provides a relatively accurate sustainability assessment that can be easily compared to other projects.

4.4.2 General Overview of the Theory Relating to the Mamdani Approach

As with the other fuzzy logic models, the Mamdani Approach is a way to interpret user input in a graphical manner that can be translated into a linguistic output. The first step in the Mamdani Approach analysis is to develop inference rules that serve as the base for
the graphical interpretation. The rules presented in Table 4 were used in the program created for this research.

<table>
<thead>
<tr>
<th>Material Rating</th>
<th>Location Rating</th>
<th>Unsustainable</th>
<th>Fairly Unsustainable</th>
<th>Moderately Sustainable</th>
<th>Fairly Sustainable</th>
<th>Sustainable</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unsustainable</td>
<td>Unsustainable</td>
<td>Unsustainable</td>
<td>Unsustainable</td>
<td>Unsustainable</td>
<td>Unsustainable</td>
<td>Unsustainable</td>
</tr>
<tr>
<td>Fairly</td>
<td>Unsustainable</td>
<td>Fairly</td>
<td>Fairly</td>
<td>Fairly</td>
<td>Fairly</td>
<td>Fairly</td>
</tr>
<tr>
<td>Unsustainable</td>
<td>Fairly</td>
<td>Moderately</td>
<td>Moderately</td>
<td>Moderately</td>
<td>Moderately</td>
<td>Moderately</td>
</tr>
<tr>
<td>Moderately</td>
<td>Unsustainable</td>
<td>Fairly</td>
<td>Moderately</td>
<td>Fairly</td>
<td>Fairly</td>
<td>Fairly</td>
</tr>
<tr>
<td>Sustainable</td>
<td>Unsustainable</td>
<td>Fairly</td>
<td>Moderately</td>
<td>Fairly</td>
<td>Fairly</td>
<td>Sustainable</td>
</tr>
</tbody>
</table>

Table 4: Mamdani Inference Rules

Based on these rules the general manipulations required by program for the analysis were constructed. The Mamdani Approach essentially functions by examining the triangular output that corresponds to each entry and then combining those triangular based figures to produce the final graph which can be defuzzified by determining the centroid of the final object.

4.4.3 How to Use the Mamdani Approach Model Program

The program created based on the Mamdani Approach requires the expert opinion of an engineer working directly with the bridge project who understands sustainability in a general sense and if familiar with the materials in the project and the project location. The Mamdani Approach Model program requires two variable values to be determined on a scale from -100 to 100. An entry of 0 would be considered moderate while -100 would be
extremely false and 100 would be extremely true for whatever variable you were examining. For the purposes on this project the two variables were location and materials. The scales would then range from extremely unsustainable in terms of location to extremely sustainable in terms of location and from extremely unsustainable in terms of materials to extremely sustainable in terms of materials on the scales from -100 to 100. The final output will be a general sustainability rating.

When first opening the Mamdani Approach Model program the following window shown in Figure 20 will appear.

![Opening Window for the Mamdani Approach Model Program](image)

Figure 20: Opening Window for the Mamdani Approach Model Program
The user will then enter the level of sustainability of the location and the level of sustainability relating to materials based on the available scale. Once the information has been entered, the user will select “Submit” to automatically generate the results graph and the appropriate defuzzification. The graph for a location rating of -70 and a materials rating of 90 would be the image shown in Figure 21.

![Mamdani Approach](image)

Figure 21: Example Output and Graph for Mamdani Example

The centroid of the graph is also provided to the user. In this case, the centroid is -0.54 which means that for the input of -70 and 90 the bridge project is classified as being slightly below fairly unsustainable. To increase the sustainability rating for this project...
the user would want to improve the location rating of this particular project. It would be
the responsibility of the engineer to determine how this could be accomplished.

4.4.4 Conclusion to the Mamdani Approach Model Program

The Mamdani Approach is an effective model for determining the sustainability rating of
a bridge project based on two input variables. For the purposes of this research, these
variables were material and location impacts of the project. This model provides a
moderately detailed sustainability rating that does not require extensive knowledge about
specifics related to the project, but it does require a general knowledge about sustainable
practices in terms of materials and location as they relate to bridges. See Appendix C:
Mamdani Approach Model Program Images for additional images of results from this
program.

4.5 Rotational Model

The process for implementing the Rotational Model outlined in “Angular Fuzzy Set
Models for Linguistic Values” by Fabian C. Hadipriono and Keming Sun (1990) was the
basis for the design of this program. Refer to the Hadipriono & Sun (1990) article for
more specific information on the fundamentals of taking a Rotational Model approach to
a topic.

4.5.1 Introduction to the Rotational Model

The Rotational Model is based on a logic rule determined by the user. This rule serves
and the basis for the sustainability assessment. In addition to defining the rule, the user
also provides information about their specific bridge project as it relates to one component of the rule. Once the program is executed, the fuzzy logic manipulation will arrive at a final result that takes into account the general rule as proposed by the user and the specific condition of the bridge in question.

4.5.2 General Overview of Theory Relating to the Rotational Model

The Rotational Model approach to fuzzy logic looks at three main components relating to Modus Ponens logic. For sustainable bridges they were determined to be the general level of recycled materials for any bridge project (represented by R), the general level of sustainability for any bridge project (represented by S) and a specific amount of recycled materials for the bridge project being examined (represented by RP). Based on this information, the program created will ultimately supply the user with a graph of the level of sustainability for the specific project (represented by SP) based on an analysis using the Rotational Model. This program is designed for someone familiar with both sustainability and generally deciphering fuzzy logic output.

To begin the user will enter the rule details and the specific sustainability level of recycled materials on the project. The rule is comprised of R and S variables and will always be:

\[ R \rightarrow S \] (the level of recycled materials implies the level of sustainability)

The user will select the components of the rule and then will enter the level of recycled materials for the specific bridge project being examined (RP). All of the values are
entered into the program using predefined fuzzy terms. The complete list of fuzzy terms relating to recyclability used in this particular program are:

- very recyclable
- recyclable
- fairly recyclable
- fairly non-recyclable
- non-recyclable
- very non-recyclable

These variables are for the R and RP values. For S or sustainability terms, the following linguistic inputs are available to the user:

- very sustainable
- sustainable
- fairly sustainable
- fairly unsustainable
- unsustainable
- very unsustainable

It should be noted that to simplify the input process for the user and to ensure that the logic in the program is used properly, the user is only able to enter the first three options on both the recyclability and sustainability lists. If the user were able to enter a value associated with the last three options or the negative options, the program would not function appropriately because these inputs would contradict the general principle of Modus Ponens used in this program. The user is able to enter the full spectrum of responses for their RP assessment. Once the inputs have been entered and the program
has computed the results the user will then defuzzify the final graph of RP which means putting the numerical graphical output graph back in to linguistic terms.

The model being used for the fuzzy input values is Baldwin’s Truth Values. These are shown in Figure 22 below.

![Baldwin Model](image)

**Figure 22: Baldwin’s Truth Values**

These are the general verbal command prefixes that trigger a specific set of linear values used in the program to generate the graphs. For this function model, \( y = x \) is True, \( y = x^2 \) is Very True, \( y = \sqrt{x} \) is Fairly True and the opposite equations relate to the false variables. This model is also used as a key at the end of the analysis to be used by the user to defuzzify the final results.

4.5.3 *How to Use the Rotational Model Program*

When the user first opens the Rotational Model Program they will see the following image depicted in Figure 23.
Figure 23: Opening Window for Rotational Model Program

Note that moderate values have been specified for the user in case they are not able to make the general assessment. The user must specify the initial parameters to begin using the program or they may continue to use the general information provided.

The following case will be the focus of this section to help demonstrate how the program functions:

\[ R = \text{Recyclable} \]
\[ S = \text{Sustainable} \]
\[ SP = \text{Fairly Sustainable} \]
In linguistic terms, this means that if the materials that are used are recyclable then the bridge will be sustainable for a general bridge project. The SP means that for the specific bridge being studied the materials used are fairly sustainable.

It should be noted that the fuzzy term selected for SP must be positive. The logic rule, which is being used in this approach is Modus Ponens as described earlier. The general form of this rule is P implies Q and P. For fuzzy logic, this rule is somewhat altered to P implies Q and some variation of P, which is still positive. If a negative term is selected for SP the result will be undecided. This will be displayed as a horizontal line at 1 for all the graphs. This is also conveyed to the user when they review the Baldwin Model Key for defuzzification. If SP is a negative term then Modus Tollens needs to be used as the logic base which is beyond the scope of this program.

Once the rule and the specific level of recycled materials are selected by the user, they will be required to select “Submit” to initiate the calculations. Once the data has been submitted, the user can generate the first graph. The graphs do not need to be generated in a specific order for the model to function properly. To generate the first graph, the user will click on the button labeled “ITFM.” The Inverse Truth Function Modification (ITFM) for the example is presented below in Figure 24.
Figure 24: ITFM Graph

The black line represents R or the general level of recyclability, and the purple line represents RP, the recyclable material level for this specific bridge project. The third line shown (light blue) is TP. TP correlates to the truth of the user supplied information for the level of recycled materials in the project. Refer to the Hadipriono & Sun (1990) article for further explanation on the truth.

After generating the ITFM the user can then generate the Lukasiewicz Implication Relation (LIR) graph by clicking on the “LIR” button. The LIR for the example is presented in Figure 25.
Figure 25: LIR Graph

The light blue line represents TP as in the previous graph. The green line represents T or the truth of the level of general sustainability for the bridge project. Refer to the Hadipriono & Sun (1990) article for further explanation.

After generating the LIR the user can generate the final graph which is the Truth Functional Modification (TFM) graph by selecting the “TFM” button. The graph shown in Figure 26 will be generated.
Figure 26: LIR Graph

On this graph the green line represents T as in the LIR. The orange line represents S or the general level of sustainability of any bridge project, and the red line represents SP which is the final result, the specific level of sustainability for the bridge project in question.

The user will be required to defuzzify the final graph. For a key to help with defuzzification the user may select the “Baldwin Model Key to Defuzzify” button. The following graph in Figure 27 will be displayed.
Figure 27: Baldwin Model Key in Program Model

The user will then follow the directions on the image in Figure 27 to defuzzify the results. For this specific example the result would defuzzify to the sustainability of the bridge is slightly less than fairly sustainable (fairly true).

4.5.4 Conclusion of the Rotational Model Program

This model is unique in that the user is required to set a rule base for its use. This gives the user more flexibility in terms of defining what sustainability means for their specific circumstance. It allows the user to adjust the program based on experience and knowledge of sustainable bridge design. In the future, the program should be expanded so that the user will only need to be a sustainability expert and will not need to understand fuzzy logic to use the program. The rules in the program will be automatically set, and the program will defuzzify the results for the user. The user will only be responsible for
entering the level of recycled materials used in a specific bridge project. At this time, this is beyond the scope of this project. See Appendix D: Rotational Model Program Images for additional images of results from this program.

4.6 Angular Model

The Angular Model uses many of the same principles as the Rotational Model but presents them in a more condensed manner. The procedure for implementing this model is outlined in the article by Hadipriono and Sun (1990). For a general understanding, it should be noted that this model is based on a combination of the processes used during the Rotational Model implementation.

4.6.1 Introduction to the Angular Model

This model is an extension of the Rotational Model. The Angular Model is very similar in its presentation requiring the user to once again, enter a rule and then a specific condition as it relates to their specific bridge project. Unlike the Rotational Model, this model allows for additional flexibility in terms of the negative spectrum of responses because it is not solely constrained by one logic rule.

4.6.2 General Overview of the Theory Relating to the Angular Model

The Angular Model uses the following equation (with specific variables for this context added) as proposed by Hadipriono and Sun (1990):

\[
\tan(\text{SP}) = \frac{\tan(S) \times \tan(RP)}{\tan(R) + \tan(RP)}
\]
Based on this equation, SP or the specific level of sustainability of a bridge can be directly determined based on the user input. No interim graphing is needed which makes this approach more simple to understand and defuzzify by fuzzy logic novices. The same principles as presented in the Rotational Model section apply to the Angular Model.

4.6.3 How to Use the Angular Model Program

The Angular Model program, like the Rotational Model program, asks for the user to enter R, S and RP (level of recycled materials, level of sustainability and level of recycled materials for the specific project). The user will enter this information into the window shown in Figure 28.
Once the user enters the information and selects the “Submit” button, the result will be automatically determined. The same conditions used for the Rotational Model were used in the following example of the Angular Model. Figure 29 would be displayed based on those conditions.
Figure 29: Angular Model

The red arrow represents $R$, the general level of recyclability, and the blue arrow which happens to be directly beneath $R$ in this example, represents $S$, the general level of sustainability. The yellow arrow is $RP$, the specific level of recyclability for the bridge project, and finally, the green arrow is the result or $SP$, the level of sustainability of the specific bridge project. As the inputs are changed the $RP$ will be adjusted accordingly.
For the Angular Model the defuzzification process is much simpler than the Rotational Model. For the example above, the user input gives the result of SP being approximately 24°. When this value is defuzzified it would represent slightly less than fairly sustainable. For this model 90° is very true, 60° is true, 30° is fairly true, 0° is neutral, -30° is fairly false, -60° is false and -90° is very false where true corresponds to sustainable and false corresponds to unsustainable.

4.6.4 Conclusion to the Angular Model Program

The Angular Model is an extension of the Rotational Model. As with the Rotational Model, the user has more control over the evaluation of the bridge project because they can control the logic rule used in the manipulation. The advantage to this model over the Rotational Model is that the Angular Model has more linguistic variables available to the user and it is not limited by one logic rule. Also as the programs currently stand, the Angular Model provides a defuzzified result to the user which can be extremely beneficial if the user is not familiar with fuzzy logic. See Appendix E: Angular Model Program Images for additional images of results from this program.

4.7 Fuzzy Logic Models Conclusion

All five of the programs presented in Chapter 4 are based on a specific fuzzy logic model. Each model uses varying inputs and parameters to assess the general sustainability of a bridge design. Those models have been utilized to be an effective assessment tool in determining the sustainability rating of a two or four lane bridge design that traverses a waterway in Columbus, Ohio. While all of the models deliver similar outputs, they each
are unique and have varying positive and negative attributes. To obtain an executable
version of the programs described in Chapter 4, please contact the author of this research.
Chapter 5: Fuzzy Model Comparisons and Contrasts

5.1 Introduction

The models defined in Chapter 4 were compared and contrasted to help evaluate their appropriateness for determining the sustainability rating of a bridge design. The Fuzzy Relation and Composition Model, the Mamdani Approach, the Rotational Model and Angular Model were all compared directly while the Triangular Model was not considered in the analysis. The Triangular Model takes a unique approach to generating the sustainability rating that relates not only expert opinion but also experience level. The other models do not take into account the level of experience of the expert so the Triangular Model was not considered in the comparisons or contrasts. Given the current state of knowledge about sustainable bridges, this model would be extremely appropriate because it only relies on an expert’s opinion of the general sustainability level, but to further enhance the idea of sustainable bridge design, the other models were determined to result in a more valuable and meaningful output.

5.2 Comparisons and Contrasts

While all four models look very different in their presentation styles, they all share similar characteristics. First, they all assess sustainability in some context using fuzzy logic principles. They all rely on the user’s opinion about their specific bridge project, and all of the inputs are very subjective in nature which is true for all fuzzy logic approaches.
The four models also share the same general output which is the sustainability rating for the bridge design in question. While the general output for all the models is similar, the input into each model differs depending on the fundamentals of the model itself.

The Rotational and Angular Models both examine sustainability specifically in terms of recyclable materials. They both take an if-then approach to their analysis that accounts for the user’s interpretation of the level of recyclable materials in their specific bridge design and how the general recyclability of materials in any project would relate to a general sustainability rating of any bridge project. While both models are similar, they are very different in that the Rotational Model can analyze a much smaller spectrum of input compared to the Angular Model. This difference is due to the mathematical natures of the models. For information on the specifics of these mathematical manipulations refer to the Hadipriono & Sun (1990) article. The Rotational Model as stated in Section 4.5 uses only Modus Ponens as a rule base while the Angular Model accounts for Modus Ponens and Modus Tollens principles of analysis. Modus Ponens in logic terminology and expressional words is represented by:

If P then Q.
P.
Therefore Q.

Modus Tollens is represented in logic by the following expression:

If P then Q.
Not Q.
Therefore Not P.
In very general terms, this means that the Angular Model can account for the negative spectrum of inputs while the Rotational Model can only relate positive input variables. There is a much greater amount of flexibility associated with the Angular Model compared to that of the Rotational Model.

Like the Rotational and Angular Models, The Mamdani Approach Model requires user interpretation of the level of recyclable materials in the bridge design, but the analysis is taken a step further because a location factor is included in the analysis of the sustainability. Also the Mamdani Approach Model has a greater spectrum of input variables available to the user compared to the other two models. In the Rotational Model, the user can only choose from three levels of recyclability and sustainability. In the Angular Model, the user has six levels to choose from. In the Mamdani Approach Model, the user has a spectrum of twenty one choices when inputting the location and materials information. This provides the user with more flexibility and judgment in their responses. It should be noted that for this greater amount of choices to be useful in any analysis, a greater understanding of sustainability by the user would be ideal.

Finally, the Fuzzy Relation and Composition Model adds another dimension to the sustainability rating output compared to the previous three models. The Fuzzy Relation and Composition Model also requires the user to input information about the feasibility of location and materials. Also this model requires the user to answer many more detailed questions about the bridge design that focus on specifics of the bridge in the material and location categories opposed to the generalizations that are required with the other models.
This can be both a positive attribute to the model because the results are more detailed and accurate, but this can be a challenging component to the system if the user is less familiar with the specifics of the bridge design.

All four models are unique in terms of their required inputs and presentation, but their overall results and interpretations are similar in nature. No one model is always perfect when interpreting linguistic data, but given the circumstances related to this research one model seems to be more appropriate at this given time than the others.

5.3 Most Appropriate Model
Based on the current state of sustainable bridge design, the most appropriate model to assess the sustainability of a bridge is the Mandami Approach Model. This model allows the user to examine two characteristics of the bridge, but it is not too focused and detailed. If a more detailed model were chosen, such as the Fuzzy Relation and Composition Model, a sustainability rating based on more details would be provided, but at this time this may be unnecessary. To use a model with more details effectively, a greater understanding of what it means to have a sustainable bridge design must be understood. Another problem with using a more detailed model at this stage of sustainable bridge assessment is that the exact rating for each component may be unknown. Up until this point, little concern was given to bridge details in terms of full sustainability so time is needed before a more detailed model will be appropriate on a general assessment scale.
The Mamdani Approach Model provides an assessment of sustainability with moderate detail. Also it is the model that allows for the most flexibility in input which would provide a greater range of classification compared to the other models. At this time, the Mamdani Approach Model is the most appropriate for determining the sustainability rating of a bridge design.
Chapter 6: Summary/Conclusions/Recommendations

6.1 Summary

Sustainability is a topic of concern today both in the United States and across the world. Every aspect of life is influenced by sustainability whether it is clothes, food or homes. Bridges should be no exception. The means to create sustainable bridges have not yet been completely defined, but small steps have been taken to achieve sustainable bridges in the future. For example, construction of bamboo bridges has been taken to new extremes through design and through the manufacturing of the material. In addition to bamboo bridges, turning to past bridge projects provides insight into how bridge design can be evolved to fit more functions than simply transportation. Inhabitable bridges are an example of how a bridge can be more than just a crossing and serve a greater need in a city. Programs such as LEED have helped to influence sustainable bridge practices by serving as a source of inspiration for a sustainable bridge rating system. These small advances in bridge design show that sustainable bridges are possible with proper innovation and planning.
The programs created for this research are designed to help evaluate the sustainability of these up and coming bridges. The programs created were:

- Triangular Model
- Fuzzy Relation and Composition Model
- Mamdani Approach Model
- Rotational Model
- Angular Model

All of these models use fuzzy logic, which allows for flexibility in this evolving genus of infrastructure. The multiple models that were created can be used together to evaluate a project which would provide an in depth examination of multiple facets of the project, or they can be used independently depending on the users knowledge of the project and their expertise in sustainability assessments. Based on the current state of sustainable bridge design, it is recommended that the Mamdani Approach Model be used because it allows for the most flexibility while still focusing on two topics of concern in reference to sustainable practices. The other models presented in this research are better suited for future evaluations when sustainable bridge criteria and parameters are better understood and defined by industry and are more widely accepted.

6.2 Conclusions

Projects such as the Bamboo Bridge at the technical University in Pereira, the Eco-Bridge in Chicago, and even the I-670 Cap in Columbus, Ohio show that more sustainable focused design is possible in the bridge community. These bridges all embody a new approach to sustainable bridge construction. Some of the projects were sustainably
focused while others naturally embodied many of the principles that are required of a project to be considered sustainable. Whichever the case, these bridges demonstrate that a new way of bridge construction is possible and that with the proper tools they can be implemented in many different settings and locations.

While more work is needed to truly be able to determine the sustainability of any bridge design, at this time the Mamdani Approach Model is the most appropriate model for assessing a generally sustainable bridge. It is specific enough examining both location and material impacts to provide accurate and meaningful results, but it allows for a wide range of inputs, which inherently gives more control to the user. As more work is done to determine the feasibility of creating a truly sustainable bridge, the other models may be more appropriate. To date, there have been great advances in what can be accomplished in a sustainable bridge project, but additional work is needed for true success.

6.3 Recommendations

The programs created in this research are the first of many steps to fully assessing the possibilities relating to the sustainability of a bridge design using fuzzy logic. For the programs to be used in the most effective and substantial way improvements need to be made. These improvements will provide an increased accuracy and level of detail to the evaluations.

In the future, the programs created to assess the sustainability of bridge projects should be enhanced with specific and customized membership functions. The membership
functions used in these programs yielded expected results, but future research into developing them may yield even more accurate and appropriate outputs. To create these specialized membership functions, data would need to be collected from a multitude of experts through surveys who would be able to assess the sustainability of any bridge design in question. The collected data would then need to be appropriately modeled to represent the correct membership function that could then be used in the programs to help in the assessment of the sustainability ratings. This would provide the most accurate analysis possible based on extensive expert input.

In terms of fuzzy logic and the specific programs, it would also be beneficial to remove any interpretation of the final results from the programs. Currently, the Fuzzy Relation and Composition Model program and the Rotational Model program both require the user to interpret graphs to defuzzify the final results. It is possible to eliminate this step and it is highly recommended for any future work on these programs relating to sustainable bridge design.

Another enhancement to the programs would be to evaluate and alter them to be appropriate for a wider scope of bridge projects. The programs for this research were designed to be used for two to four lane vehicular bridges over a waterway in Columbus, Ohio. By focusing on this location, the programs could be more tailored leaving fewer areas of estimation and confusion. If further research was done to assess the programs use in other areas and for other types of bridge projects, the programs may be able to have a greater impact on the bridge industry as a whole.
Adding additional variables to aid in the assessment of the bridges could enhance each program individually. Currently, the Fuzzy Relation and Composition Model accounts for the most variables related to the bridge design. The other programs would be more affective if they, too, accounted for more specific details relating to the projects. It is recommended that the addition of these variables first begin with the Mamdani Approach Model. Adding additional variables would be relatively simple based on the fundamentals of the program, but for this research, it was simply out of the scope of this project given the time constraints.

Finally, a connection between this research and Greenroads (University of Washington & CH2M HILL, 2010) could be made. Greenroads is a performance metric that was established with a joint effort from the University of Washington and CH2M HILL. Greenroads is currently in its early implementation stage, but it focuses on rating and analyzing new or major rehabilitation (reconstruction) roadway projects on a system very similar to that of LEED. For Greenroads, a sustainable roadway would be a “roadway project that has been designed and constructed to a level of sustainability that is substantially higher than current common practice.” In its current form, Greenroads only gives a brief mention to applying this metric to bridges but for almost any major roadway project bridges plan a key role. It would be a great benefit to infrastructure if programs such as LEED and Greenroads also considered bridge design in detail in their analysis. To do this, perhaps a separate rating system needs to be developed that could be used by Greenroads’ projects that have a bridge. Another option would be to clearly mention that
bridges are held to the same standards as the roadways. At this current time, this may be an unrealistic goal, but it should be a standard to aim for in the future.

These recommendations would help to make the developed programs more applicable to sustainable bridge design on a larger scale. If all these recommendations were implemented, it is possible that these programs would have more influence on sustainable bridge design and the infrastructure community in general. The expansion may even foster sustainable enhancements to other forms of infrastructure.
References


Appendix A: Triangular Model Program Images

Figure 30: Triangular Input 1

Figure 31: Triangular Output General 1

Figure 32: Triangular Output Final 1
Figure 33: Triangular Input 2

Figure 34: Triangular Output General 2

Figure 35: Triangular Output Final 2
Appendix B: Fuzzy Relation and Composition Model Program Images

Figure 36: Fuzzy Relation and Composition Input 1

Figure 37: Fuzzy Relation and Composition Output 1
For each item choose the linguistic value that best corresponds to how the element relates to the bridge project. Once all the values have been determined, select Submit to process the data. To view the results click on the Fuzzy Relation Graph tab when it appears.

Location:
- Choosing a location to minimize environmental impact: Low
- Choosing a location that is not ideal for other construction: Medium
- Choosing a location close to local building materials: Low

Materials:
- Establishing practices to minimize construction pollution: Low
- Using minimal construction resources: Medium
- Reusing or recycling waste materials: High
- Using recycled materials in the construction: Medium
- Using non-recycled materials that use recycled materials: High

Feasibility of Location: Low
Cost of Location: Expensive
Feasibility of Using Materials: Low
Sustainability of Materials Used: Unsustainable

Figure 38: Fuzzy Relation and Composition Input 2

Figure 39: Fuzzy Relation and Composition Output 2
Appendix C: Mamdani Approach Model Program Images

Figure 40: Mamdani Sample 1
Figure 41: Mamdani Sample 2

Figure 42: Mamdani Sample 3
Appendix D: Rotational Model Program Images

Figure 43: Rotational Model ITFM 1
Figure 44: Rotational Model LIR 1

Figure 45: Rotational Model TFM 1
Figure 46: Rotational Model ITFM 2

Figure 47: Rotational Model LIR 2
Figure 48: Rotational Model TFM 2
Appendix E: Angular Model Program Images

Figure 49: Angular Model Sample 1
Figure 50: Angular Model Sample 2

Figure 51: Angular Model Sample 3