Intelligent Decision Making Tool for Small Wind Turbines in Ohio

THESIS

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By

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Abstract

Sustainable energy use is an important factor in the construction industry’s future. Commercial and residential buildings currently consume large amounts of energy in construction and operation. Nearly all our buildings depend on a conventional grid system powered by fossil fuels that contribute to global warming. Civil engineers are obligated to find and use alternative power sources for buildings while meeting the growing demand for clean energy.

Much research has been done on the use of renewable energy sources, with solar and wind the fastest-growing. Solar and wind energy are the fastest-growing renewable energy resources. Wind power has been harnessed on a large scale by wind farm construction, using large turbines beyond the fiscal reach of an individual owner. Small wind energy systems offer opportunities for investment and growth, suitable for individual property owners to harness wind energy affordably.

This research consists of developing an Intelligent Decision Making Tool to recommend the most suitable small wind turbine for users in Ohio. In order to help this process, this research has developed an Intelligent Decision Making Tool to recommend the most suitable turbine for Ohio users. This tool will take all aspects of the user’s property and budget into consideration, resulting in a recommendation for the most appropriate wind
turbine for the site, an explanation of the logic used with advantages and disadvantages of turbine installation, the total cost associated with the turbine, and the LEED points earned. A feasibility check on a fuzzy model can be carried out by the user in which he/she can select both the rules and facts.

Further improvements for greater accuracy in the tool include accounting for wind turbulence, wind shear, surface roughness, and including more detailed readings of local wind conditions. These improvements will make the Intelligent Decision Making Tool more helpful to the small wind turbine buyer.
Dedication

This research is dedicated to my family
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CHAPTER 1: INTRODUCTION

1.1 Introduction

Industrial and domestic energy demand has been increasing steadily for the last forty years. This rise in demand is driven by the rapid increases in consumption and population. Civil engineers are challenged to design buildings that are energy efficient and green to help meet the rising cost of energy due to limited non-renewable sources and population pressure.

This research involves in developing an Intelligent Decision Making Tool to determine the most suitable wind turbine for Ohio. This chapter explains the goals, objectives, tasks, scope and limitation of this research.

1.2 Goal, Objective and Tasks

The goal of this research is to reduce the dependency of commercial and residential buildings on the conventional grid system increase the use of renewable sources of energy. Most U.S. buildings rely on fossil fuels for energy; a change to renewable energy will lower greenhouse gas emissions.
The objective of this research is to develop an Intelligent Decision Making Tool (IDMT) that would determine the wind turbine most suited for different locations in Ohio by taking into account the cost, power output, and wind speed at a particular location and a particular building model and its surroundings.

Three tasks were identified to achieve this objective. The first task was to study the available small wind turbines, their type and method of installation, application and their costs and rate of return. The second task was to choose the most appropriate wind turbine, including some with a horizontal axis and others with a vertical axis, taking into consideration the cost and power output associated with each. Lastly, the turbines were compared in the computer model using different scenarios, with a detailed description for each turbine at different locations.

1.3 Scope and Limitations

This research is focused on the use and performance of small wind turbines for commercial, residential and agricultural property in Ohio. Twelve horizontal axis and seven vertical axis wind turbines were selected for their similarity to those turbines readily available in Ohio. They were categorized according to their rotor diameters, cost, and type of turbine. Wind speed data from seven weather stations in Ohio operated by the National Climatic Data Center was gathered to calculate the potential power output from different turbines at different locations. The IDMT would then recommend a wind turbine from the list of 19 wind turbines used in this research, based on the user’s
selection criteria. The IDMT also would carry out a feasibility test using a fuzzy logic
tool, the angular model.

However, this research does not consider the total life cycle and sustainability of the wind
turbine. We currently determine sustainability by the savings that result from turbine
installation. We compare the amount of renewable energy the building uses with amount
of fossil fuel energy. But we do not consider the total life cycle of a wind turbine by
accounting for the amount of energy and materials used to manufacture it. A complete
life cycle analysis would need to consider the total energy use and related emissions
involved in all the stages of a turbine’s production, use and disposal. Some turbines also
would be connected to a battery system; hence, we would need to consider the type of
batteries used and their method of disposal.

The IDMT has several other limitations in its analysis. The decision making tool does not
consider the effect of wind turbulence, surface roughness and the weight and number of
blades of the different turbines when determining the turbine’s annual power output.
Another is the calculation of the wind speed, which is an approximation of speed
obtained from the weather station closest to the turbine’s installation location. Taking
additional weather stations into account and obtaining more wind speed data would
increase the accuracy of the IDMT’s results and also increase the number of locations and
users where it could be applied. Finally, the IDMT does not take into consideration the
structural strength of the roof or ground where the turbine will be placed. A structural
engineer can carry out the analysis, where he/she would consider the dead load and wind
load imposed by the turbine and calculate if extra reinforcement is needed. The addition
of this analysis to the Intelligent Decision Making Tool would provide more accurate and detailed results about the cost benefit of wind turbine installation.

This tool would be more efficient and effective in the analysis and application of small wind turbines if the limitations listed above were removed, by providing more detailed results. Obtaining wind speed and turbine data for multiple locations would increase the geographic scope and usefulness of this tool.

1.4 Organization

The steps taken to develop the IDMT are discussed in the following chapters. The literature search includes the study of the wind turbine market and the different types of wind turbines currently available. The turbines used in this research are similar to current turbines on the market along with their cost and size. The method and logic model used in the IDMT is also discussed along with the content and parameters used. The feasibility test is carried out on the angular model. The method and use of the angular model is addressed in later chapters.
CHAPTER 2: LITERATURE SEARCH

2.1 Introduction

Energy is a very important factor for economic development. Due to rapidly industrializing countries and increasing population, the demand for electricity has doubled between 1973 and 2003 and is expected to increase by another 40% by 2020 (International Energy Association 2008). According to the International Energy Agency, geothermal, solar and wind energy account for 0.7% of the power produced in 2008. Non-renewable resources such as gas, oil and coal account for 94.6% of the power produced in 2008.

Figure 1 illustrates the share of total primary energy supply in the United States.

Figure 1: Share of total of primary energy in the United States (Source: International Energy Agency)
Population growth affects energy consumption. The world’s population is expected to grow to 8.3 billion people by 2030 – an average increase of 1% per year. Rising population and industrial growth is directly proportional to energy demand. Between 1971 and 1990, each 1% increase in global Gross Domestic Product was accompanied by a 0.66% increase in primary energy consumption. Between 1990 and 2000, the corresponding increase in demand dropped to only 0.44%, but it rebounded to 0.68% in 2000-2006. Over the last ten years crude oil prices have increased by threefold from $33.33 per barrel to $100 per barrel in 2010 (International Energy Association 2008). Due to the future population growth, the demand for energy will increase rapidly. If dependence on conventional fossil fuels as an energy source continues, energy costs will grow exponentially and demand will exceed supply.

We are still very dependent on oil, coal and natural gas resources to meet our energy demands. Dependency on these non-renewable resources causes large amounts of greenhouse gas emissions into the atmosphere, contributing to global warming. Generation and consumption of energy is responsible for adding 50 to 60 percent of greenhouse gases into the atmosphere. (Fox and Anaya-Lara 2007, 2 - 7)

2.2 Energy Consumption by Buildings in the United States

In the United States, buildings account for 36% of the country’s primary energy use. U.S. homes contribute to 22% of our national energy use. Lighting in U.S. buildings accounted for 31% of commercial building energy. The demand for electricity and
powering homes and buildings has been increasing steadily over the past 50 years. Energy consumption by buildings in the United States in 2002 contributed to (Kibert 2008, 162 - 163):

- 47% of U.S. sulfur dioxide emissions
- 22% of nitrogen oxide emissions
- 35% of carbon dioxide emissions

The shift from the fossil fuel powered grid network to renewable energy installation on buildings would reduce the operational costs of the buildings and their dependency on the conventional grid system. For example the wind turbines on the World Trade Center in Qatar create up to 15% of power utilized by both the buildings.

2.3 Renewable Sources of Energy

Over the last decade there has been a significant rise in investment in renewable sources of energy. The most common renewable sources are hydro-electric power, solar power, geothermal power and wind energy (U.S Department of Energy 2009).

The advantages of renewable energy are that it is sustainable, non-polluting and can be generated anywhere in the world. However, renewable energy sources have high initial costs such as construction costs, purchase of large open land, and equipment costs. Some renewable energy sources may also cause visual and noise pollution as in the case of wind turbines or hydroelectric power stations. (Nelson 2009, 13 - 14)
Since large renewable energy projects require such a large capital investment, most individuals cannot afford them. Thus, opportunities are available for smaller scale projects. Figure 2 shows wind turbines installed at a wind farm.

Figure 2: Wind turbines on a wind farm (Source: National Renewable Energy Laboratory)
Unlike other renewable sources of energy such as geothermal and hydroelectric power stations that require water or steam to function, solar photovoltaic systems and wind energy sources do not require water to produce electricity, which is a huge savings on water and costs of operation. Solar and wind sources of energy also have a major advantage in that they can produce energy most parts of the world upon installation of the equipment.

Solar electric systems are constructed of specialized hardware that collects solar radiation and converts this energy to electricity. The major drawback with solar power systems is the number of sunlight hours available; the greater the amount of solar radiation, the higher the efficiency of the solar power systems. (Texas Comptroller Accounts, 2008, 137 - 150)

Wind power systems are mechanical devices that convert kinetic energy from the wind into electricity. They consist of a main rotor shaft, blades and an electricity generator. For wind power systems to operate efficiently, wind speeds must be adequate for the specific wind turbine. The wind speeds must not be either too low or too high due to the factor of cut-in wind speed and cut-out wind speed (Fox Anaya-Lara 2007, 2 - 11).

### 2.4 Cut-In Wind Speed and Cut-Out Wind Speed

Cut-in wind speed is the speed that is required for the wind turbine to start to generate electricity. The cut-in wind speed varies for every turbine. In urban environments where the average wind speeds are low, wind turbines capable of energy production at
low wind speeds will have an advantage in terms of total energy production. (Wineur 2011)

Cut-out wind speed is the wind speed that causes the turbine to shut down. At very high wind speeds such as in storms or hurricanes the turbine usually shuts down to prevent damage to the rotor blades, the generator or other components. No power is generated at wind speeds above the cut-out wind speed. The cut-out wind speed would vary for all turbines and it ranges from 60 to 100 mph wind speeds.

The conditions used to control and minimize rotor speed are tilt control, where the turbine’s rotor is shifted from the direction of strong winds, and passive control, where the rotors of the turbine would automatically shut down (Wineur 2011).

2.5 Background Study

Large wind turbines (usually with a capacity of more than 1MW) can also be placed in oceans and lakes and hence, we have offshore wind farms. These wind turbines are very large in size, usually with a height of about 90 feet and a blade diameter of more than 60 feet. They usually require wind speeds of more than 6 m/s to start producing electricity and generally cost more than a million dollars to construct and operate depending upon the construction location. Though a lot more power can be harnessed from the larger wind turbines, the cost, size and noise associated with conventional wind turbines makes it very difficult for an average person to purchase them. They are therefore usually purchased by cities, townships, state governments or the federal government. Due to the size and cost of these turbines the ability to harness wind energy on a smaller and
individual level is limited. Therefore smaller and more compact wind turbines are more suitable to the general consumer who can purchase them and install them with relative ease.

Most turbines are designed for already existing buildings, and can be placed on the roof of the building or on a tower near the building. Some buildings are designed such that the wind turbines are incorporated onto the building as part of their structure. A good example is the World Trade Center in Doha, Qatar whose towers were designed so they create a pressure gradient between the buildings and the wind speed increases as it flows through the buildings. Three horizontal axis wind turbines are incorporated onto three sky bridges connecting the two towers. The wind turbines here are expected to create 11 – 15% of the energy requirements of both buildings. Figure 3 shows the two towers and the sky bridges connecting them and wind turbines mounted on them. (Richard F Smith 2005) Another example similar to the WTC in Qatar is the Strata Tower in London, where the building was originally designed to have three 30-foot wind turbines incorporated on the building roof top to produce 50 MW of electricity every year which would account for 8% of the energy needs of the building.
New research and innovative design is creating new kinds of wind turbines that can be incorporated to the existing plan of buildings. A good example is the ridgeblade that is designed to be incorporated on the ridge of a hip roof. The ridgeblade’s turbine blades are incorporated in the roof ridge so electricity is generated when the wind blows. They also help with the ventilation of the house. (The Power Collective)

As shown in the example of the Qatar World Trade Center, where the buildings were designed to create a pressure gradient to increase the wind speed, the windcube is a turbine that is constructed with the same physics to create a pressure difference such that
the wind speed increases as it comes into contact with the wind turbines. As shown in figure 4, the shroud of the windcube amplifies the wind speed to produce more power from a smaller footprint. (Get Smart Energy)

Figure 4: Windcube (Source: Get Smart Energy, Ohio)
2.6 Small Wind Turbine Systems

Small wind energy systems can make a significant contribution to our nation’s energy needs. Various wind turbines have been developed for small scale use that can be installed on buildings, houses, factories and farms. The power generated from small scale wind turbines would greatly differ due to size of the rotor (a bigger rotor generates more power), height of turbine placement, and the wind speed at that location (Small Wind Electric Systems, An Ohio Consumer’s Guide, 2007).

Small wind turbines produce DC current, and use special equipment to make the generated electricity useful. As shown in figure 5, a residential grid connected to a wind energy system would include a controller, storage batteries, an inverter and wiring. An inverter is a device that converts the direct current (DC) produced by the generator of a wind turbine to alternating current (AC) which can be exported to a grid network. Alternating current is the standard form of household electricity available. This electricity can be used to power general household products (shown in Figure 6) or DC appliances can be used instead. Direct current can also be stored in batteries. When energy is created it is most often stored as direct current energy. A controller is a device that monitors the voltage in the batteries and sends power to the batteries to recharge them or sends the power to the grid network when the batteries are full.

A stand-alone system (systems that are connected to the battery and not the utility grid) would require batteries to store excess power generation when the winds are calm. They
would also need a charge controller to keep the batteries from over charging (Small Wind Electric Systems, An Ohio Consumer’s Guide, 2007).

The wind turbine can also be connected directly to the grid where a meter would record the amount of power supplied to the grid. A grid-connected wind turbine can reduce the consumption of utility-supplied electricity for lighting, appliances, and electric heat. If the turbine cannot deliver the amount of energy required, the utility lines make up the difference. This form of application would be greatly useful for areas where the grid wires can be extended to the local point of use and the meter can be connected at the point of connection between the turbine and the grid. When the wind system produces more electricity than required, the excess electricity is then sold to the utility company. A meter is installed along with the turbine and its purpose is to allow the electric meters of customers with generating facilities to turn backwards when their generators are
producing more energy than the customers’ demand.

Figure 5: Wind turbine DC Power to AC power conversion system. (Source: Castle Energy Services, Ohio)

2.7 Types of Small Wind Turbine Systems

Small wind turbines can be classified into Horizontal Axis Wind Turbines (HAWTs) and Vertical Axis Wind Turbines (VAWTs).

A HAWT’s rotors rotate parallel to the wind stream and the ground. Most commercial wind turbines are HAWTs. Horizontal axis machines have some distinct advantages such
as low cut-in wind speed and easy furling. In general, they show relatively high power efficiency. HAWTs can be classified into downward wind and upward wind turbines as shown below. Yaw devices have to be incorporated to small HAWT to rotate the wind turbine to the direction from which the strong winds are coming from (Sathyajith, Mathew 2006). Significant amount of room must be available for the yaw device to work effectively and the turbine to rotate around with ease. In this research 12 HAWTs have been used. Figure 6 shows a HAWT.
A VAWT’s rotors are almost perpendicular to the wind stream and the ground. The VAWT can receive wind from any direction. Hence complicated yaw devices can be
eliminated. The generator and the gearbox of such systems can be housed at the lower level of the turbine which makes the tower design more simple and economical.

Wind direction is not of great concern when placing a VAWT since the design of the VAWT is such that it would operate efficiently on wind speeds from all directions. Figure 7 shows a VAWT installed on a hipped roof. From this figure we can observe that the blades of the turbine are designed such that they come into contact with wind speeds from all directions.
2.8 Factors Affecting Wind Turbine Output

The factors that affect a wind turbine’s power output include atmospheric conditions, installation mechanical problems, wind speed, height of turbine placement, wind turbulence, and wind breakers or obstacles in front of the wind turbine.
Wind speed is the single most important factor in determining the performance of a wind turbine: the greater the wind speed, the greater the power generated by the wind turbine. Thus, it must be certain that the placement site has winds strong enough (greater than 5m/s) for the turbine to generate sufficient power. In theory the higher the wind turbine is placed, the more wind speed is attained. As the height increases at which the turbine is placed, the more likely it is that the turbulent air flow produced near the ground by the surface roughness of the terrain over which the wind is flowing can be avoided, as well as excessive ground drag which lowers wind speed. Direct obstacles and wind breakers that may appear above the plane over which the wind is flowing must also be avoided. Smoother winds which are less turbulent are more favorable.

In densely built up areas, wind speeds tend to be high but also very turbulent. Turbulent flow presents challenges due to the rapidly changing wind direction. This produces extra stress on the turbine blades and slows energy production particularly if the turbine cannot react quickly to turn itself to take advantage of the new wind direction.
Figure 8: Wind turbulence illustration

A machine that copes well with wind turbulence or an area of low turbulence in the urban environment is most desirable. Building tops or open areas on the ground such as agricultural fields, school playing grounds or parks show a great deal of promise.

2.9 Noise

Noise is a very significant factor with building-integrated wind turbines. The amount of noise that a wind turbine can produce can affect the consumer’s purchase decision. Thus it is essential to know the amount of noise a turbine produces when in operation at different wind speeds. Noise is higher at higher wind speeds due to excessive movement
of the blades. It is desirable to know the maximum wind speed at a location, as that helps determine the expected noise level from a wind turbine. (Wineur 2011)

Wind turbines generate two types of noise: aerodynamic and mechanical. Aerodynamic noise is generated by the blades passing through the air. Depending on the turbine model and the wind speed, the aerodynamic noise may sound like buzzing, whooshing, pulsing, and even sizzling. Mechanical noise is generated by the turbine’s internal gears. Noise from the blades and gearbox can be reduced from careful attention to design and manufacture of the components. (Sathyajith, Mathew 2006) VAWTs are regarded as more silent than HAWTs generally because they operate at lower speeds.

2.10 Zoning

Zoning limitations apply at different locations depending on the size, noise and appearance of the wind turbine, though variances for some zones can be obtained. For example, a height jurisdiction could apply to some residential areas. Height restrictions vary for different zoning ordinances and should be researched before installing a turbine. In addition to zoning issues, there could be a problem of NIMBY (not in my back yard). For example, neighbors can object to a wind turbine blocking their view or they may be concerned with the noise. Usually permits can be attained from the local building inspector and the noise level that a turbine produces can be attained from the manufacturer (Small Wind Electric Systems, An Ohio Consumer’s Guide, 2007).
2.11 Wind Turbine Location

Wind speeds can vary at the same location. In addition to ascertaining the annual wind speeds, it is helpful to find the prevailing wind directions at a location. For example, higher wind speeds can be found at the top of a hill or the top of the highest building in the area, as compared with the lower side of the hill or the building. If the wind turbine is to be located in a complex terrain, the height of placement becomes important. If any obstructions (trees, houses, sheds and so on) are in the way of wind flow path, a wind turbine with a yaw system may be considered. Another consideration is possible future obstruction caused by new building construction or trees that have not reached their full height. As a general guideline, turbines usually need to be placed upwind of buildings and trees, and they need to be at least 30 feet above anything within a 300-foot radius. Turbines also have to be made accessible for repair and maintenance. This would not be a problem for turbines placed on rooftops as turbines can be easily accessed However, if turbines are mounted on towers, there needs to be enough room to raise and lower the tower for maintenance. If the tower is guyed, there must be enough room for guy wires to be placed. (Small Wind Electric Systems, An Ohio Consumer’s Guide, 2007)

Whether the system is stand-alone or grid-connected, the length of the wire running from the turbine to the grid or battery must be considered. A substantial amount of electricity can be lost as a result of the wire’s resistance; the longer the wire the more electricity can be lost. Using a longer or larger wire will also increase installation costs. Wire run losses are greater with direct current (DC) than with alternate current (AC). Hence with a
longer wire run, power would be saved if the direct current was inverted to alternate current. (Wind Power Integration, Connection and System Operation Aspects)

Figure 9: Wind turbine location (Source: Small Wind Electric Systems, An Ohio Consumer's Guide)

2.12 Costs and Grants

Costs of small wind turbines have generally been quite high due to research, testing and manufacturing costs. These products are relatively new and many of them are still in the testing phase. Most manufacturers put a higher price on these systems to recover the cost of the investment they have made. Wind turbine systems cost anywhere from $1,000 to
$400,000 depending on the power output they produce. The costs of the turbines used in this research are shown in Table 4.

The wind turbine costs include the cost of the equipment and installation. Installation cost is usually lower if the turbines are installed on rooftops rather than as on a tower. A tower installation’s cost would include construction of the tower’s foundation and tower installation, the wind turbine and a larger area of land if guy wires are needed. As discussed earlier, installation costs would also increase if the turbine is placed further away from the grid system or the battery pack. Installation costs would vary greatly depending on local zoning, permitting and utility interconnection costs.

The length of the payback period - the time before the savings resulting from the system equal the cost of the system itself - depends on the system chosen (rotor diameter), the wind speeds at the turbine location and electricity costs in the area.

There has been significant progress in funding green energy in the U. S. State governments are providing various incentives for installation and use of green energy to reduce the dependency on fossil fuels. Government incentives are also available at the federal level where the federal government provides a 30% tax credit on all wind turbine purchases for residential and commercial use. The U.S. Department of Agriculture offers grants to agricultural producers and rural small businesses to purchase and install wind turbines. The grant amount in this case is a percentage of total project cost, with a maximum grant amount of $500,000, depending on the size of the farm and need for the grant. The State of Ohio has the highest number of incentives available for the purchase and use of green energy. Some of the incentives in Ohio include: Green Columbus Fund;
Green Energy of Ohio; PACE Financing and Energy Conservation of Ohio, to name a few. (Database of State Incentives for Renewable & Efficiency)

2.13 Maintenance

Maintenance costs of a wind turbine, also known as the running costs, will vary depending upon the wind speed and power generated. According to a study carried out by Mike Anderson (1996), the average maintenance cost of a wind turbine is 1.5 cents per kwh produced.

2.14 LEED Certification and Points

The LEED (Leadership in Energy and Environmental Design) rating system is the most commonly used building-sustainability rating system in the United States, developed by United States Green Building Council (USGBC). A certain number of points need to be achieved, using a variety of energy efficiency and renewable energy measures as well as innovation and design, before the building can attain the status of LEED certified. The LEED rating system works on a point system as shown in Table 1 and Table 2. Points are earned based on the development in each of the categories as shown in Table 1 and certified based on the total points as shown in Table 2. (Kibert 2008, 55-65)
Table 1: LEED Points Table. (Source: Sustainable Construction, Green Building Design and Delivery, by Charles J. Kibert)

<table>
<thead>
<tr>
<th>Areas of Eligible for Points</th>
<th>Points</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sustainable Sites</td>
<td>26</td>
</tr>
<tr>
<td>Water Efficiency</td>
<td>14</td>
</tr>
<tr>
<td>Energy &amp; Atmosphere</td>
<td>35</td>
</tr>
<tr>
<td>Materials &amp; Resources</td>
<td>10</td>
</tr>
<tr>
<td>Indoor Environmental Quality</td>
<td>15</td>
</tr>
<tr>
<td>Total Possible Points</td>
<td>110</td>
</tr>
</tbody>
</table>

Table 2: LEED Certification Points Table (Source: Sustainable Construction, Green Building Design and Delivery, by Charles J. Kibert)

<table>
<thead>
<tr>
<th>LEED Points</th>
<th>Certification</th>
</tr>
</thead>
<tbody>
<tr>
<td>40 – 49</td>
<td>Certified</td>
</tr>
<tr>
<td>50 – 59</td>
<td>Silver</td>
</tr>
<tr>
<td>60 – 79</td>
<td>Gold</td>
</tr>
<tr>
<td>80 +</td>
<td>Platinum</td>
</tr>
</tbody>
</table>

LEED points are earned based on the amount of renewable energy that is used to power a building, with a maximum of 8 LEED points. Table 3 below shows the number of points a building can earn by using renewable energy.
2.15 Conclusion

The literature review draws the conclusion that the amount of energy utilized from the conventional grid system is enormous in relation to renewable energy sources used. Sustainable construction of buildings not only requires environmentally friendly materials to be used but also that the building design allows for the incorporation of the new technologies of renewable energy. The carbon footprints of buildings would be greatly reduced with the utilization of renewable energy sources. Assuming that each household in the U.S. installs a wind turbine, the overall reduction in the energy demand from the conventional grid system would be enormous.
Various factors must be considered before installing wind turbines on a property. A site evaluation must be carried out and the net amount of wind speed calculated so that there is enough cut-in wind speed. In addition to wind speed, a user must also consider the zoning laws and permits to install a wind turbine. NIMBY is an issue that varies from place to place and would need to be addressed before turbine installation. On the LEED metric system, a total of eight points can be earned by installing wind turbines on a building.
Chapter 3 - Wind Speed calculations used in the IDMT

3.1 Introduction

Wind speed is a very important factor when determining power output from wind turbines. In cities and urban areas where small wind turbines will be placed, it is usually difficult to determine wind speed due to turbulence caused by buildings and obstructions that change the properties of the wind flow.

When wind is flowing over an open area and approaches the boundaries of built-up areas, it encounters surface roughness created by buildings (Mansoureh, 2009). Near the ground, wind experiences friction and wind speed is reduced more steeply and its turbulence increases.

Wind speed can be measured by the use of anemometers. Anemometers must be placed at the height where the turbine will be placed and the wind speed and direction should be recorded for over a year so that the wind speed pattern can help predict the turbine’s power output. Using an anemometer to predict wind speed is usually a lengthy process and the data attained might not give accurate reading of the wind patterns.

Wind speed data can be obtained from the Department of Energy, National Climatic Data Center and other local weather stations. Figures 12 and 13 are the wind resource maps of the United States and Ohio obtained from the Department of Energy and AWS. From the
map we can observe that Ohio has about 350 to 500 kWh/year per m² of potential wind energy depending on the location.

Figure 10: Wind resource map of the United States (Source: National Renewable Energy Laboratory)
Figure 11: Wind resource map of Ohio (Source: National Renewable Energy Laboratory)
3.2 Weather Stations in Ohio

Using anemometers to determine wind speed and direction can be a lengthy process and the results obtained may not be very accurate. It is usually difficult to determine future wind speed trends due to lack of historical wind speed data. Wind speed data from the closest weather station is a reasonable substitute for most users. Davenport’s equation helps users determine wind speeds at their location with respect to the surroundings. Equation 3.2 requires information about the height of the anemometers’ placement at each weather station and a description of the surroundings. Wind speed data for Ohio was gotten from the National Climatic Data Center. Most of their weather stations are at airports and anemometers are placed at a height of 10 meters (30 feet) above the ground and the surrounding area is an open terrain with scattered obstacles generally at a height of less than 10 meters (30 feet).

The list below shows the Ohio weather stations used in this research:

- Columbus
- Dayton
- Akron
- Cleveland
- Mansfield
- Toledo
- Youngstown
The average wind speeds attained from the weather stations above are shown in Table 4.

Table 4: Wind Speed Data

<table>
<thead>
<tr>
<th>CITY</th>
<th>YEARS</th>
<th>JANUARY</th>
<th>FEBRUARY</th>
<th>MARCH</th>
<th>APRIL</th>
<th>MAY</th>
<th>JUNE</th>
<th>JULY</th>
<th>AUGUST</th>
<th>SEPTEMBER</th>
<th>OCTOBER</th>
<th>NOVEMBER</th>
<th>DECEMBER</th>
<th>AVERAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>AKRON</td>
<td>54</td>
<td>11.60</td>
<td>11.10</td>
<td>11.40</td>
<td>10.80</td>
<td>9.10</td>
<td>8.40</td>
<td>7.60</td>
<td>7.20</td>
<td>8.00</td>
<td>9.30</td>
<td>10.00</td>
<td>11.30</td>
<td>9.70</td>
</tr>
<tr>
<td>CLEVELAND</td>
<td>61</td>
<td>11.20</td>
<td>11.80</td>
<td>11.00</td>
<td>10.00</td>
<td>8.50</td>
<td>7.80</td>
<td>7.40</td>
<td>7.20</td>
<td>8.90</td>
<td>9.90</td>
<td>11.00</td>
<td>12.00</td>
<td>10.50</td>
</tr>
<tr>
<td>CANTON</td>
<td>59</td>
<td>11.40</td>
<td>11.10</td>
<td>11.70</td>
<td>11.30</td>
<td>9.70</td>
<td>8.80</td>
<td>7.90</td>
<td>7.30</td>
<td>8.30</td>
<td>9.80</td>
<td>11.00</td>
<td>11.10</td>
<td>9.90</td>
</tr>
<tr>
<td>TOLEDO</td>
<td>57</td>
<td>11.00</td>
<td>10.50</td>
<td>11.00</td>
<td>10.90</td>
<td>9.50</td>
<td>8.40</td>
<td>7.50</td>
<td>7.10</td>
<td>7.90</td>
<td>8.60</td>
<td>10.20</td>
<td>10.40</td>
<td>9.40</td>
</tr>
<tr>
<td>YOUNGSTOWN</td>
<td>53</td>
<td>11.40</td>
<td>11.10</td>
<td>11.30</td>
<td>10.60</td>
<td>9.40</td>
<td>8.40</td>
<td>7.70</td>
<td>7.40</td>
<td>8.10</td>
<td>9.20</td>
<td>10.00</td>
<td>11.10</td>
<td>9.70</td>
</tr>
</tbody>
</table>

3.3 Determining Wind Speeds at Different Locations

Small wind turbines are placed at different locations according to the user’s needs. It would be very difficult to determine the accurate wind speed at every user’s individual location because of different site properties, varying air densities, and varying heights of turbine placement. In this research, Davenport’s (1960) equation is used to determine wind speeds in an urban outset of varying site properties. Davenport’s equation, shown below, computes the wind speed at different heights with respect to the closest weather station and the different types of terrain (Mansoureh, 2009).

\[
\frac{V_z}{V_G} = \left(\frac{Z}{Z_G}\right)^\alpha
\]

Equation 3.1

Where:

\[V_z = \text{mean wind speed at the height of } h \text{ meters in the study terrain (m/s)}\]
\( V_G = \) mean wind speed at height \( Z_G \) (Gradient height) at the top of the boundary layer of the study site, above which the speed is assumed to be constant (m/s)

\( Z = \) the height for which the wind speed \( V_Z \) is computed (m)

\( Z_G = \) the height at which gradient velocity \( V_G \) is first observed (layer thickness) in the same terrain (m)

\( \alpha = \) an empirical exponent which depends on the surface roughness, stability and temperature gradient.

Table 5 shows the typical values of \( Z_G \) and \( \alpha \) for mean wind speeds over four types of terrain.

Table 5: Values for \( Z_G \) and \( \alpha \) for Mean Wind Speeds Over Four Terrain Types (Source: The Estimation of Wind Speeds, By Mansoureh Tahbaz)

<table>
<thead>
<tr>
<th>Terrain Category</th>
<th>Description</th>
<th>Exponent ((\alpha))</th>
<th>Layer Thickness (Z_G) (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Large city centers, in which at least 50% of buildings are higher than 21m over a distance of at least 2000 meters upward</td>
<td>0.33</td>
<td>460</td>
</tr>
<tr>
<td>2</td>
<td>Urban, suburban, wooded areas, and other areas with closely spaced obstructions compared to or larger than single-family dwellings (over a distance of at least 2000 meters upwind)</td>
<td>0.22</td>
<td>370</td>
</tr>
<tr>
<td>3</td>
<td>Open terrain with scattered obstacles generally less than 10 meters height</td>
<td>0.14</td>
<td>270</td>
</tr>
<tr>
<td>4</td>
<td>Flat, unobstructed areas exposed to wind flowing over a large water body (no more than 500 meters inland)</td>
<td>0.10</td>
<td>210</td>
</tr>
</tbody>
</table>
We use equation 3.1 to estimate wind speed in different urban areas with different density and terrain roughness. Equation 3.2 is a result of Equation 3.1. (Mansoureh, 2009)

\[
\frac{V_{\text{met}}}{V_Z} = \left(\frac{\text{Met}_H}{\text{Met}_G}\right)^{\alpha_{\text{met}}} / \left(\frac{Z_Z}{Z_G}\right)^{\alpha} \]

Equation 3.2

\(V_Z\) = Mean wind speed at a height \(Z\) meters in the study terrain (m/s)

\(V_{\text{met}}\) = Mean wind speed at the height of \(H\) meters in the meteorology station (m/s)

\(Z_G\) = Gradient height at the top of the boundary layer of the study terrain

\(Z_Z\) = Height \(Z\) meters at the study terrain (m)

\(\text{Met}_H\) = Standard observation height of \(H\) meters in the meteorology station (m)

\(\text{Met}_G\) = Gradient height at the top of the boundary layer of the meteorology station

\(\alpha_{\text{met}}\) = Exponent of the roughness of the meteorology station

\(\alpha\) = Exponent of the roughness of the study terrain

Equation 3.2 requires the height of the anemometer at each weather station. Anemometer placement heights are obtained from the weather stations run by the National Climatic Data Center. Users choose the weather station closest to their location and also choose the description of their location to feed in the layer thickness and exponent values to the equation. The user’s choice of weather station in the IDMT determines the standard observation height of \(H\) meters in the meteorology station (\(\text{Met}_H\)), the exponent of the roughness of the meteorology station (\(\alpha_{\text{met}}\)) and mean wind speed at the height of \(H\) meters in the meteorology station in m/s (\(V_{\text{met}}\)).
3.4 Wind Turbines Used in the IDMT

Table 6 lists the wind turbines used in this research. 19 horizontal and vertical axis wind turbines were chosen for their similarity to those on the local market. The turbines are differentiated based upon their costs, rotor diameters, and type of turbine and availability.

Table 6: List of Turbines Used in the IDMT

<table>
<thead>
<tr>
<th>Turbine</th>
<th>TYPE</th>
<th>Rotor Diameter (ft)</th>
<th>Height (ft)</th>
<th>Power output in Kwh/yr at 12 mph wind speed</th>
<th>Cost ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turbine A</td>
<td>HAWT</td>
<td>69</td>
<td>N/A</td>
<td>183,000 Kwh/yr</td>
<td>$333,000</td>
</tr>
<tr>
<td>Turbine B</td>
<td>HAWT</td>
<td>3.5</td>
<td>N/A</td>
<td>432 Kwh/yr</td>
<td>$995</td>
</tr>
<tr>
<td>Turbine C</td>
<td>HAWT</td>
<td>7</td>
<td>N/A</td>
<td>1,200 Kwh/yr</td>
<td>$2,900</td>
</tr>
<tr>
<td>Turbine D</td>
<td>HAWT</td>
<td>9</td>
<td>N/A</td>
<td>2,400 Kwh/yr</td>
<td>$3,600</td>
</tr>
<tr>
<td>Turbine E</td>
<td>HAWT</td>
<td>15</td>
<td>N/A</td>
<td>6,300 Kwh/yr</td>
<td>$8,500</td>
</tr>
<tr>
<td>Turbine F</td>
<td>HAWT</td>
<td>12</td>
<td>N/A</td>
<td>4,500 Kwh/yr</td>
<td>$19,000</td>
</tr>
<tr>
<td>Turbine G</td>
<td>HAWT</td>
<td>21</td>
<td>N/A</td>
<td>13,900 Kwh/yr</td>
<td>$35,000</td>
</tr>
<tr>
<td>Turbine H</td>
<td>HAWT</td>
<td>63</td>
<td>N/A</td>
<td>164,000 Kwh/yr</td>
<td>$235,000</td>
</tr>
<tr>
<td>Turbine I</td>
<td>HAWT</td>
<td>12</td>
<td>N/A</td>
<td>5,000 Kwh/yr</td>
<td>$32,000</td>
</tr>
<tr>
<td>Turbine J</td>
<td>HAWT</td>
<td>15</td>
<td>N/A</td>
<td>6,400 Kwh/yr</td>
<td>$37,000</td>
</tr>
<tr>
<td>Turbine K</td>
<td>HAWT</td>
<td>18</td>
<td>N/A</td>
<td>12,000 Kwh/yr</td>
<td>$45,000</td>
</tr>
<tr>
<td>Turbine L</td>
<td>HAWT</td>
<td>30</td>
<td>N/A</td>
<td>30,000 Kwh/yr</td>
<td>$78,000</td>
</tr>
<tr>
<td>Turbine M</td>
<td>VAWT</td>
<td>5</td>
<td>4.1</td>
<td>1,100 Kwh/yr</td>
<td>$7,100</td>
</tr>
<tr>
<td>Turbine N</td>
<td>VAWT</td>
<td>7.5</td>
<td>15.1</td>
<td>1,900 Kwh/yr</td>
<td>$13,750</td>
</tr>
<tr>
<td>Turbine O</td>
<td>VAWT</td>
<td>13</td>
<td>5.2</td>
<td>7,500 Kwh/yr</td>
<td>$29,000</td>
</tr>
<tr>
<td>Turbine P</td>
<td>VAWT</td>
<td>39</td>
<td>40</td>
<td>150,000 Kwh/yr</td>
<td>$29,500</td>
</tr>
<tr>
<td>Turbine Q</td>
<td>VAWT</td>
<td>6</td>
<td>6</td>
<td>5,500 Kwh/yr</td>
<td>$10,000</td>
</tr>
<tr>
<td>Turbine R</td>
<td>VAWT</td>
<td>5</td>
<td>9.05</td>
<td>5,000 Kwh/yr</td>
<td>$25,000</td>
</tr>
<tr>
<td>Turbine S</td>
<td>HAWT</td>
<td>20</td>
<td>N/A</td>
<td>250,000 Kwh/yr</td>
<td>$229,000</td>
</tr>
</tbody>
</table>

3.4.1 Power Expected from the Wind Turbine

Wind turbine manufacturers rate the power output expected from their turbine with respect to wind speed. They usually provide a power curve and the annual energy output curve that indicates the amount of power their turbines produce every year. The power
curve is a graph that indicates the amount of electricity produced by a wind turbine at different wind speeds.

The power output of a wind turbine can be measured by Equation 3.3 or by field measurements where an anemometer is placed near the turbine and the power produced is measured against the oncoming wind speed. Power curves are based on measurements in areas with low turbulence intensity, with the wind coming directly towards the front of the turbine. Local turbulence and complex terrain (e.g. turbines placed on a rugged slope) may mean that wind gusts hit the rotor from varying directions. It may therefore be difficult to reproduce the power curve exactly in any given location. (Small Wind Electric Systems, An Ohio Consumer’s Guide, 2007)

Figure 12: Example of a power curve VS wind speed for Urbangreen 1K wind turbine (Source: Castle Energy Services)
The IDMT provides the user with the power output of a wind turbine with respect to the location, wind speed and height at which the turbine is placed. We can use Equation 3.5 to get a preliminary estimate of the performance of a particular wind turbine. This equation has been used to determine the approximate annual power output from a turbine (Small Wind Electric Systems, An Ohio Consumer’s Guide, 2007 & Engineering 167).

Power Equation Derivation (Equation 3.5)

Max Power Equation = \((\frac{1}{2} \times \rho \times V^3 \times \pi \times \text{radius}^2)/1000\) (Mtrs, kgs, M/S) Eq. 3.3

Actual Power Equation = \((\frac{1}{2} \times \rho \times C \times K \times V^3 \times \pi \times \text{radius}^2)/1000\) (Ft, lbs, mph) Eq.3.4
Derive constant to yield power in kilowatts (K)

\[(\frac{1}{2} \cdot \rho \cdot V^3 \cdot \pi \cdot \text{radius}^2) \cdot 1000\] (in meters, kilograms, kg/m³)

\[(\frac{1}{2} \cdot (\rho \cdot 16) \cdot (V \cdot 0.45)^3 \cdot \pi \cdot (\text{radius} \cdot 0.3048)^2) / 1000\] (Convert meters, kilograms, m/s to feet, pounds & mph)

\[(\frac{1}{2} \cdot \rho \cdot V^3 \cdot \pi \cdot \text{radius}^2 \cdot 0.133) / 1000\] (K = 0.133)

\[\frac{1}{2} \cdot \rho \cdot V^3 \cdot \pi \cdot \text{radius}^2 \cdot 0.000133\] (feet, pounds, mph)

Taking the maximum power coefficient into consideration:

\[
\text{Power} = k \cdot C_p \cdot \frac{1}{2} \cdot \rho \cdot A \cdot V^3 \] ..........................................................Equation 3.5

Where:

P = Power output in kilowatts

C_p = Maximum power coefficient

k = 0.000133 A constant to yield power in kilowatts.

V = Wind speed in mph

A = Rotor area swept (ft²)

\(\rho\) = Air density in lbs/ft³

The maximum power coefficient \(C_p\) lies between 0.25 and 0.45 and can be calculated using the graph on Figure 14 (Engineering Graphics 167). A matlab program developed in Engineering Graphics 167 utilizes the following graph to calculate the exact value of \(C_p\) with respect to the turbine dimensions and angular speed. The Betz Limit is the
maximum possible power coefficient where the wind turbine blades rotate constantly all year round (Engineering Graphics 167).

Figure 14: Power Coefficient for Horizontal and Vertical Axis Wind Turbine (Source: Engineering Graphics 167)
The air density of a location varies according to the temperature and height above sea level. The average height above sea level was obtained for the locations used in the IDMT and the air density used in the program is maintained at 59°F.

The air densities used in the IMDT are:

Columbus: 0.0737 lbd/ft³
Akron: 0.0734 lbd/ft³
Cleveland: 0.0743 lbd/ft³
Youngstown: 0.0738 lbd/ft³
Mansfield: 0.0727 lbd/ft³
Toledo: 0.0744 lbd/ft³
Dayton: 0.0741 lbd/ft³

The rotor area swept by the turbines varies depending if the turbine is a horizontal axis or a vertical axis. For a horizontal axis wind turbine, the rotor area swept is calculated as follows:

\[ A = \pi D^2/4 \] \hspace{1cm} \text{Equation 3.6}

On the other hand the rotor area swept by a vertical axis wind turbine would be calculated as follows:

\[ A = D \times H \] \hspace{1cm} \text{Equation 3.7}

The equations differ for the different turbines as the rotor area swept by the turbines depends on how the turbines are mounted and the motion at which they rotate.
This method of calculation does not take into account the site variables such as wind shear, turbulence, air density at the site’s altitude and turbine specific output. This calculation gives a generic evaluation of turbine output.

Equation 3.3 is used to calculate the annual power output of the turbine with respect to the wind speed in the area. The rotor diameters for each of the turbines are already programmed into the system; therefore, upon selection of both a turbine and a location, the program calculates the annual power output for the chosen turbine.

3.4.2 Payback Period

The payback period of a wind turbine is an important factor that users consider before purchasing one. Calculating the payback period requires the total cost of the turbine and expected annual savings from the turbine. Other factors include rotor diameter, turbine performance, and the wind speed at the turbine location. The turbine’s payback period is calculated using the following equation

\[
\text{Payback period} = \frac{\text{Total cost}}{\text{Expected annual savings}}
\]

The total cost would include the cost of the equipment, installation costs, yearly maintenance costs, minus the grants gotten to install the turbine.

\[
\text{Total costs} = \text{Cost of equipment} + \text{Installation costs} + \text{Maintenance cost/year} - \text{Grants}
\]

3.5 Conclusion

The power output from each of the turbines used in this research is worked out on a monthly basis depending upon the wind speed that comes in contact with the turbine.
The annual energy output is the maximum possible energy output from the turbine.

Davenport’s equation is used to calculate wind speed at different terrains according to the user’s preferences, where the user would select the height at which the turbine shall be placed, location and terrain.
CHAPTER 4: DEVELOPMENT OF INTELLIGENT DECISION MAKING TOOL

4.1 Introduction

The Intelligent Decision Making Tool (IDMT) required several steps in its design. The first was developing the architecture of the system, the second was a survey of industry experts to gain pertinent information, and the third was a literature search for existing small wind turbines on the market. The architecture used in the IDMT and the flow chart used to generate exact matches is also discussed.

4.2 Research Methods

Experience and knowledge are vital for the successful completion of an engineering project. New engineers may lack the expertise that comes from field experience, so in order to successfully complete a task, often seek input from experts in the field, in addition to engineering literature survey results. So that the IDMT might provide the most accurate results, two outside experts, David Walters from Castle Energy, Ohio and Mike Cironi from Green Energy Technologies were consulted for their input on the necessary concepts and their application on the project’s decision-making computations. Additional information regarding the specifications and performance of small wind turbines currently on the market was gained by searching industry literature. The above helped clarify the parameters for the IDMT. The turbines used in this research are similar
to wind turbines available on the local market. Wind turbine size, performance and costs used in this research are similar to the turbines on the local market. Wind turbine data was attained from Castle Energy Services.

The experts used in this research, Mark Cironi and David Walters are wind turbine specialists with extensive experience and knowledge on wind turbine installation and performance.

4.2.1 Intelligent Decision Making Tool Architecture

Figure 15 shows the architecture of the IDMT. The decision process begins with the potential wind turbine owner, called the user, collecting the evidence related to his/her site and feeding it to the interface of the system. As mentioned above, this information includes the future location of the turbine, its purpose, the cost, the output desired, the nature of the site, and wind speeds.

The interface component of the IDMT provides a means for the user to communicate comfortably and effectively using. The input criteria for the interface are efficiency, user friendliness, clearness and absence of complication. The output criteria of the IDMT are precision and completeness.

The data entered is then passed through the decision tree support mechanism and a conclusion in the decision tree is reached through exact matching. The decision tree can be changed and updated by the knowledge engineer as new information arises. After a turbine has been selected the output is displayed to the user via the interface. The
decision tree links to the explanation facility where the explanation facility explains the reasoning behind a given conclusion.
Figure 15: Architecture of intelligent decision making tool
4.2.2 Stages in the Development of the Intelligent Decision Making Tool

The following steps were taken to develop the Intelligent Decision Making Tool:

- Define scope and limitations of the IDMT
- Acquire background and technical information from literature search.
- Consult domain experts, knowledge engineers and computer programmers.
  Knowledge engineers include knowledge modelers and programmers that assist in logic development, data structure, software development and documentation.
- Develop the architecture of the IDMT
- Construct decision tree support mechanism
- Represent knowledge

4.3 Decision Tree use in Intelligent Decision Making Tool

Table 7 illustrates the decision tree used in the IDMT in the decision making process. The exact matching method is used in the decision making process. The parameters in the IDMT are divided according to the use, power output, budget, and grid or battery connection, obstructions in a 20 meter radius, and tower or roof connection.

Turbine use can be described as follows: Commercial use includes high rise buildings, business parks, colleges and universities, shopping malls and so on. Commercial buildings have a significantly higher power demand. Residential use includes turbines for houses and residential areas. Residential use turbines are generally smaller in size when compared to commercial and agricultural use turbines and must produce much lower
levels of noise. The cost of turbines for residential use is usually lower than commercial and agricultural use turbines. Agricultural use turbines can be much larger in size when compared to other uses due to the availability of land and grant funding. Turbines can also be used to power streetlights and boats.

Since the cost of electricity varies by area or zone (commercial/residential/agricultural), it is vital that the user give this input at the beginning. Choosing the proper option aids the IDMT to determine the prevailing cost of electricity of the user’s building. In addition, it also helps the IDMT to determine the payback period of the turbine and savings made from installing the turbine.

A turbine’s power output varies depending on the rotor diameter of the turbine, type of the turbine and the mechanical soundness of the individual turbines. This variation ranges from 0 to 1000 kwh/yr to more than 60,000 kwh/yr. Since turbine diameter varies from one to another, the power output would be different for all turbines.

An important piece of data is the cost of the turbines. This varies depending on the turbine’s power output, its lifetime, its rotor diameter and also its use. In the market, the brand name and marketing by turbine manufacturers also contributes to the cost of the turbine.

The connectivity of a turbine is also an important factor. Some turbines can be connected only to a battery pack, a grid or both. For example, turbines B, C, D and E can only be connected to a battery pack and not the grid system. These turbines are usually much smaller in size and produce smaller amounts of electricity or a separate inverter needs to
be purchased to connect these turbines to the grid. They are useful on agricultural land or small scale uses where grid connected power cannot reach.

The obstructions around the turbine’s placement in a 20-meter radius are an important issue. Some turbines will not function effectively with obstructions because they tend to break the wind flow. HAWTs could not function very well in an obstructed area because of the turbine’s yaw system. Explain the yaw system briefly, if not here, back in the earlier section. The yaw system works well in an area where the turbine can rotate freely. In a compact area a VAWT operates better because it does not require a yaw system. The last step in the flow chart is the turbine’s placement. Some turbines can be mounted only on a tower or only on a rooftop, some on both.

Key for table 7

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Table 7: Decision Tree Diagram

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<td>Agricultural</td>
<td>&gt; 20000 - 40000</td>
<td>20000 - 30000</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Other</td>
<td>&gt; 40000 - 60000</td>
<td>30000 - 40000</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>&gt; 60000</td>
<td>40000 - 50000</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
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<td></td>
<td>50000 - 75000</td>
<td></td>
<td></td>
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<tr>
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<td></td>
<td></td>
<td>&gt; 75000</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
4.4 Conclusion

The IDMT is developed using the components and architecture illustrated in this chapter. The selection parameters were carried out by interviewing experts in the industry and doing a literature search in small wind turbines. The event tree diagram uses the concept of exact matching.

The wind speed calculations discussed in the previous chapter are incorporated into the IDMT for the different locations and the power output from the turbine is calculated.
CHAPTER 5: INTELLIGENT DECISION MAKING TOOL

5.1 Introduction

The Intelligent Decision Making Tool (IDMT) helps to determine the most suitable small wind turbine for residential, commercial, agricultural and other small scale use in Ohio. It is a program made for consumers to assist them in narrowing down their selection of a wind turbine by answering a series of questions related to their site, budget and preferences. This chapter discusses the computer program developed, the interface system and series of questions asked to the user.

5.2 Intelligent Decision Making Tool

The IDMT begins with a welcome page that asks a user to state the use of the wind turbine. Uses are classified into commercial use, residential use, agricultural use and other small scale use. Some turbines are specifically developed for residential or commercial use due to their cost, size and noise produced. This option narrows the set of turbines that would be recommended to the user. This option also helps to determine the cost of the building’s electricity, the costs saved by the installation of the turbine and the payback period. The cost of electricity in Ohio for commercial buildings is 9.91 cents/kwh, for residential buildings 11.43 cents/kwh and for all other sectors 9.06
cents/kwh.

For example, if a user wants to install a wind turbine on his/her property (commercial property) in Columbus, Ohio, he/she selects ‘commercial’ in the purpose tab as shown in Figure 16.

![Welcome page and uses section for program](image)

**Figure 16:** Welcome page and uses section for program

The next step is a query about the location of the turbine placement. Here the user picks the closest location to the turbine placement from the drop-down menu in the program. The drop-down menu box contains seven locations in Ohio. Since we are using
Davenport’s Equation (Chapter 3), the heights (\(\text{Met}_H\)) at which the anemometers are placed at the weather stations, the layer thickness (\(\text{Met}_G\)) and the exponent of the roughness of the meteorology station (\(\alpha_{\text{met}}\)) have already been input into the program. Hence selecting a location from the drop down menu box would enter the \(\text{Met}_H\), \(\alpha_{\text{met}}\) and \(\text{Met}_G\) to calculate the wind speed estimate at the turbine location. The user would also choose the parameter that closely resembles the wind turbine site. He/she would be given four options from which to choose the one that most closely matches site description. This option determines the exponent of roughness (\(\alpha\)) and layer thickness (\(Z_G\)) at the site of turbine placement. The location selection choice in the drop down menu box also determines the air density for each of the locations in the IDMT. This is useful to predict the turbine’s power output as indicated in Equation 3.3. The air densities for each location at a temperature of 59°F have been uploaded into the program.

Continuing with our example of the user who wants to install a wind turbine on his/her property in Columbus, the user now selects Columbus from the drop down menu and selects the urban area radio button (second radio button) as shown in Figure 17.
After selecting the turbine’s location, the user enters the building information. Here the user is asked a series of questions about the building such as the current power consumption of the building, how much power output does the user expect from the wind turbine, the consumer’s budget, if the user is connecting the turbine to a grid or battery, the user’s judgment on the condition of the roof top or the ground surface and if there are any obstructions near the site that might affect the wind flow. This series of questions provides a set of parameters that help the IDMT hone in on the most suitable wind turbine for the user’s individual case.
When the user selects the current power consumption, he/she will be given a range of power outputs in kilowatt hours to select from, as the power consumed by a building cannot be constant and varies from time to time. This choice helps to determine the cost and power saved upon installing the wind turbine and the LEED points earned by the building. The LEED points earned by a building are calculated as a percentage of renewable power used by the building. The program calculates the power output from the turbine for the entire year with respect to the wind speed for each month. It then takes the mid-point of the range of power consumption the user has chosen to calculate the percentage power contributed by the turbine and hence, the LEED points earned.

In the example shown below, the user wants to install a wind turbine in Columbus. They then select their building parameters as shown in Figure 18. They plan to install the turbine on a flat roof at a height of 50 meters as shown in Figure 19.
The next question concerns turbine placement. The turbine can be placed on a rooftop (Figure 19) or mounted on a tower (Figure 20). Upon selecting the turbine’s location, the explanation facility provides an explanation on the ‘do’s and don’ts’ of mounting the turbine on the different types of roofs or towers in the results page (Figure 23).
Figure 19: Roof selection page

Figure 20: Tower selection page
The height of turbine placement is requested at this stage since this will help determine the wind speed and the cost of installation. The higher the turbine’s placement, the more efficiently it will run. There is a trade-off in a greater height, as the cost of installation would be higher. For example, if a turbine is installed on a 120-foot tall building, a crane or a helicopter is needed to place the turbine on the roof. The IDMT alerts the user to this cost increase. There is no set figure to relate the cost of installation with the height of the building, as the factors would vary from case to case. Thus the user should ask an engineer for a more accurate installation cost estimate.
The user has the option of using the wind speed data obtained from local weather stations and computed by Davenport’s Equation to calculate the wind speed at that location. However, wind speed from Davenport’s Equation is only an approximation of the wind speed at the turbine location. The user is also given an option of entering the wind speed data manually if he/she has an anemometer placed on their site or has gotten wind speed data from another source.

Figure 21: Wind speed page
As a result of the choices that the user has made in the previous tabs, the IDMT determines the most suitable small wind turbine(s) for the user. Once the turbine(s) has been recommended, the labels, buttons and radio buttons associated with the turbine are highlighted as shown in Figure 22.

After the user selects a wind turbine recommended to him/her the next step in the IDMT will be to determine the total cost of the turbine. The total cost of installing the wind turbine would be:

Total cost of turbine = Cost of turbine + permit cost + cost of installation – grants
available.

The costs of the turbine and the preliminary cost of installation are similar to costs of current turbines on the market. The permit cost would vary for each location and the use of the turbine, and so would the grants available to install the turbine. The user can get grants from various organizations at the state and federal level. A link to apply for grants for installing a turbine has been provided on this page (Figure 23). Upon selection of a turbine the preliminary costs and grants are entered and the user has the option to change the costs and to work out the total cost, depending on their individual case.

The total cost of installation given here is subject to change depending on the state of the ground or roof of the location, the height of the building, the distance to the grid from the turbine and whether or not grants are available. These costs would vary in every case and thus the exact cost must be attained by consulting an engineer, though the averages costs have been entered for the user as shown in Figure 23.
Figure 23: Costs page

Figure 24: Turbine power output
The annual power output by the wind turbine is calculated using Equation 3.3 in Chapter 3. The power output is determined by the wind speed for that month and the turbine selected by the user. Annual power output is used to calculate the payback period, the maintenance costs and possible LEED points earned. The power output curve shown in Figure 24 is an approximation.

Figure 25: Results page

The results page of the IDMT includes the total cost of the turbine, maintenance cost, estimated annual savings, LEED points earned and a description of the possible
drawbacks to the turbine’s installation.

Returning to the example of the user who wants to install a wind turbine in Columbus, Ohio, the user will use the wind speed data recorded in the IDMT. Upon clicking ‘recommend’ the user is recommended turbine P and turbine S as shown in Figure 22. The total cost is approximated for the user and he/she can view the turbine performance for his/her location as shown in Figure 24. The results for this location are shown in Figure 25 where the user would earn 8 LEED points; the payback period would be 5.45 years. A further recommendation is given to the user to install the turbine on a flat roof and other considerations include the height of the building and the obstructions around the turbine’s location.

5.3 Conclusions of Intelligent Decision Making Tool

The IDMT uses the parameters and architecture as discussed in the Chapters 3 and 4. The event tree and the parameters used are dependent on personal judgment and experts in the industry. The expert has the ability to change the parameters of the IDMT and add more turbines to the system with relative ease. The series of questions and answers presented to the users helps the IDMT draw a conclusion. The questions in the system act as the parameters for the IDMT. The power output, cost of maintenance and the LEED points earned are provided to the user based on the type of turbine he/she selects. See Appendix A: IDMT Program Images for additional images of results from this program.
CHAPTER 6: FUZZY ANGULAR MODEL

6.1 Introduction

The user can implement a feasibility test after he/she has selected the turbine that best meets his/her needs. The feasibility test uses the fuzzy angular model. Fuzzy logic is used because the variables can be quantified and the decision making process can be carried out using partial matching. In the IDMT, the decisions were made with exact matching and not partial matching.

The angular model uses the fuzzy set angular method to interpret the fuzzy linguistic values. The angular model provides a method to easily solve and interpret variables.

The variables arise from the individual preferences of the user, as the feasibility of a wind turbine would vary depending upon location, aesthetics, power output and other considerations. A turbine suitable for one location may not be suitable at another as user preferences might vary. Hence, a model that provides for individual preferences is most appropriate to determine feasibility.

6.2 Angular Model

In the following example, a feasibility test is carried out using the angular model. The user will compare the power output of the turbine with its dependency on the grid to
determine feasibility. The fuzzy set angular model can be applied to fuzzy logic “modus 
ponens” and “modus tollens” deduction techniques. In relation to the modus ponens and 
modus tollens, we employ fuzzy logic operations such as the truth functional 
modification (TFM) and the inverse truth functional modification (ITFM), where some 
calculation procedures are required. The linguistic variables used for the model and 
their corresponding angles are given in Section 6.3.

This method of approximate reasoning was developed by Zadeh. We apply approximate 
reasoning fuzzy modus ponens and modus tollens deduction techniques. The following 
derivation of the angular model is based on Fabian C. Hadipriono and Keming Sun 
(1990, Angular fuzzy set models for linguistic values). A modus ponens relationship is 
commonly stated as: \([P \land (P \rightarrow G)] \rightarrow G\). The following is a modus ponens relationship:

\[
\begin{align*}
\text{Antecedent 1: } & (p \text{ is } P) \supset (g \text{ is } G) & P, P' \subset U \\
\text{Antecedent 2: } & (p \text{ is } P') & G, G' \subset V \\
\text{Consequent: } & Q (g \text{ is } G) \text{ is } \tau_G \text{ and } (g \text{ is } G) \text{ is } \tau_B \subset T
\end{align*}
\]

where the symbol \( \supset \) is a representation of the implication relation between \((p \text{ is } P)\) and \((g \text{ is } G)\); \(p\) and \(g\) are the names of objects; \(P\) and \(P'\) are fuzzy sets in the universe of 
discourse \(U\), while \(G\) and \(G'\) are fuzzy sets in universe of discourse \(V\); \(Q (g \text{ is } G)\) means 
“the truth of \((g \text{ is } G)\)” ; \(\tau_G\) is the new truth fuzzy set value in truth space \(T\) and the symbol 
“\( \subset \)” denotes ‘ a subset of’.  

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When we have a fact that shows \( P' = P \) the consequent is realized, but when \( P' \) is not equal to \( P \), the fuzzy inference is in order. This form of inference is known as Fuzzy Modus Ponens Deduction (FMPD). The purpose of the FMPD is to find the value of \( G' \).

A fuzzy modus tollens deduction can be stated as \([ (P \rightarrow G) \wedge \neg G ] \rightarrow \neg P \)

Antecedent 1: \((p \text{ is } P) \supset (g \text{ is } G)\) \quad P, P' \subseteq U \quad (6.4)

Antecedent 2: \((g \text{ is } G')\) \quad G, G' \subseteq V \quad (6.5)

Consequent: \(Q \text{ (p is } P)\) is \( \tau_P \) and \((p \text{ is } P')\) \( \tau_P \subseteq T \) \quad (6.5)

where \( \tau_P \) is the new truth fuzzy set value in the truth space \( T \). This method is called the Fuzzy Modus Tollens Deduction (FMTD) which is reduced to modus tollens when \( P' \) is not \( P \) and \( S' \) is not \( S \). This can be used to find the truth value of a certain proposition that has an implication for relation with a second proposition when information for the second proposition is available.

Truth Functional Modification (TFM) and Inverse Truth Functional Modification (ITFM) would need to be used to solve for FMPD and FMTD.
6.2.1 Truth Function Modification

TFM is a logic operation that can be used to modify the membership function of a linguistic value in a certain proposition with a known truth value. TFM operation is described below:

We have proposition \( \gamma \) that can be allocated truth value restrictions, then

\[
\gamma: (p \text{ is } P) \text{ is } \tau_P; \quad P \subseteq U; \quad \tau_P \subseteq T \tag{6.7}
\]

where the truth restriction \( \tau_P \) is the value of \( T \). The modification of this proposition yields the following:

\[
\gamma': (p \text{ is } P'); \quad P' \subseteq U \tag{6.8}
\]

Suppose that \( \mu_P (z) \) and \( \mu_{P'} (z) \) are membership functions of proposition \( P \) and \( P' \) respectively and \( \mu_{\tau_P} (t) \) is the membership function of the truth restriction \( \tau_P \). Suppose that the angles of \( P \) and \( \tau_P \) are \( x \) and \( y \) respectively as shown in Figure 26, the membership function would now be:

\[
\mu_{P'} (z) = \mu_{\tau_P} [\mu_P(z)] \tag{6.9}
\]
The membership function can be solved as:

\[ \mu_P(z) = z \tan x \quad \mu_{\tau P}(t) = t \tan y \]  \hspace{1cm} (6.10)
Substituting equation 5.10 into 5.9

\[ \mu_{P'}(z) = \mu_{\tau P} [z\tan x] = z\tan x \tau y \]  

(6.11)

Hence, \( \mu_{P'}(z) = z\tan w \)  

(6.12)

Where, \( \tan w = \tan x \tan y \)  

(6.13)

### 6.2.2 Inverse Truth Function Modification

The Inverse Truth Function Modification (ITFM) can be used to obtain the truth values of a conditional proposition. Say we take a proposition: \( \gamma: (p \text{ is } P) \), but it is unknown from given data (\( p \text{ is } P' \)). The truth proposition \( \gamma \) can be calculated as follows:

\[ Q(p \text{ is } P/p \text{ is } P') = \tau P; \tau P \subset T; P, P' \subset T \]  

(6.14)

where \( \tau P \) is the new truth restriction of the truth value for fuzzy set \( P \). The membership function of the new truth value, \( \mu_{\tau P}(t) \) can be obtained from the following:

\[ \mu_{\tau P}(t) = \mu_{\tau P} [\mu_{P}(z)] = \vee [\mu_{P'}(z)] \]  

(6.15)

where \( \vee \) denotes the value where \( z \) is maximum. The proposition \( \mu \) would now become \( \mu': (p \text{ is } P) \text{ is } \tau P \). Therefore, the proposition described above can be written as:

\[ \mu: (p \text{ is } P)/(p \text{ is } P') ; \quad P, P' \subset U \]  

\[ \mu: (p \text{ is } P) \text{ is } \tau P: \quad \tau P \subset T \]  

(6.16)
Suppose that the membership function $P$ and $P'$ are characterized by the angles $x$ and $x'$ as shown in Figure 27. The membership function $\mu_P(z)$ and $\mu_{P'}(z)$ can be expressed as:
\[ \mu_P(z) = z \cdot \tan x; \text{ and } \mu_P'(z) = z \cdot \tan x' \] (6.17)

Substituting equation 6.17 into equation 6.15, the membership function \( \mu_{\tau P}(t) \) can be characterized by the angle \( y \):

\[ \mu_{\tau P}(t) = \mu_{\tau P}[\mu_P(z)] = \mu_{\tau P}[z \cdot \tan x] = z \cdot \tan y \]

and \( \mu_{\tau P}(t) = \lor[\mu_{\tau P}(z)] = \lor[z \cdot \tan x'] \)

so that \( z \cdot \tan y = z \cdot \tan x' \). For \( z \neq 0 \), we have:

\[ \tan y = \frac{\tan x'}{\tan x} \] (6.18)

and \( \mu_{\tau P}(t) = t \cdot \tan y = t \cdot \tan x'/\tan x \) (6.19)


### 6.2.3 Fuzzy Modus Ponens Deduction

We consider the propositions in equation 6.1 where:

- Antecedent 1: \((p \text{ is } P) \Rightarrow (g \text{ is } G)\), \(P, P' \subseteq U\)
- Antecedent 2: \((p \text{ is } P')\), \(G, G' \subseteq V\)

Through the ITFM, antecedent 1 and 2 can be combined to give us:

\[ \gamma: (p \text{ is } P) \Rightarrow (g \text{ is } G) \] (6.20)
The truth value of \((g \text{ is } G)\), i.e. \(\tau_G\), can be obtained by the modus ponens deduction. The mathematical membership function of the truth value \(\tau_G\) is given by:

\[
\mu_{\tau_G}(n) = V[\mu_{\tau_P}(m)^\land \mu_1(m, n)] \tag{6.21}
\]

where \(m\) and \(n\) are the elements (truth levels) of the truth space \(T\) and \(T'\) of the propositions \((p \text{ is } P)\) and \((g \text{ is } G)\) respectively. \(\mu_1(m, n)\) is the truth implication relation function of the proposition \((p \text{ is } P)\) is \(\supset\) \((g \text{ is } G)\) and the symbol \(\land\) denotes minimum conjunction of \(\mu_{\tau_P}(m)\) and \(\mu_1(m, n)\).

For the angular model, we need to define a new Lukasiewicz truth implication relation \(\mu_1(m, n)\). The traditional Lukasiewicz truth implication relation of \(P\) and \(G\) is defined as follows:

\[
<P \supset G> = \text{MAX}[0, <G> - <P>]; \tag{6.22}
\]

where \(<P\), \(<G>\) and \(<P \supset G>\) are the membership functions of \(P\), \(G\), \(P \supset G\) respectively. Hence the truth implication relation in angular models is given as

\[
\mu_1(m, n) = n - m; \quad m, n \geq 0 \tag{6.23}
\]

Using Blockley’s (1980) approach, instead of using \((p \text{ is } P)\) and \((g \text{ is } G)\) we use \(P\) and \(G\) respectively. Hence our equation 6.1 becomes:

\[
[P \supset G] \text{ is } \tau_1; \quad P, P' \subset U
\]
P' is $\tau_2$; \hspace{1cm} G, G' \subset V

\begin{align*}
\text{Q}(G) \text{ is } \tau_G \text{ and } G' ; \quad \tau_G \subset T \quad \tag{6.24}
\end{align*}

where $\tau_1$ and $\tau_2$ are the truth implication relation $\mu_1(m, n)$ and of proposition (p is P'). We use $z . tanP$, $z . tanP'$ and $t . tanG$ to represent the membership function $\mu_P(z)$, $\mu_{P'}(z)$, $\mu_{\tau G}(t)$ respectively to simplify the description. We will use the fuzzy set values such as $P = \mu_P(z) = z . tanP$, $P' = \mu_{P'}(z) = z . tanP'$ etc. to represent as functions because the proposition is usually expressed by its membership function. Using the TFM and ITFM, the proposition P and P' can be combined as:

$$
\begin{align*}
\text{Q}(P/P') = \tau_P = \text{ITFM} \left[ P/\text{TFM} (P', \tau_2) \right] \\
= \text{ITFM} \left\{ P/\{P'\tan \tau_2\} \right\} \\
\text{That is } \tau_P = t . tanP'. tan \tau_2 / tanP \quad \tag{6.25}
\end{align*}
$$

The proposition from equation 6.24 can be rewritten as:

$$
\begin{align*}
\text{[P is } \tau_P \supset G\text{] is } \tau_1 ; \quad P \subset U; G, G' \subset U
\end{align*}
$$

\begin{align*}
\text{Q}(G) \text{ is } \tau_G \text{ and } G' ; \quad \tau_G \subset T \quad \tag{6.27}
\end{align*}

\(\tau_G\) can be calculated by equation 6.21. It can be rewritten as:

$$
\begin{align*}
\mu_{\tau G}(n) = V \{ \mu_{\tau P} (m) \land \text{TFM}[ \mu_1(m, n), \tau_1 ] \} \\
\text{Substituting equation 6.23 into equation 6.27, we obtain:}
\end{align*}
$$
\[ \mu_{\phi}(m) = m.\tan_\phi = TFM[(n - m), \tau_1] \]

\[ = (n-m) \tan_1 \]

and \( m = n \tan_1 / [\tan_1 + \tan_\phi] \) \hspace{1cm} (6.29)

Hence we have:

\[ \mu_{\tau G}(n) = n.\tan_\tau G = \mu_{\phi}(m) = m. \tan_\phi \]

\[ = n.\tan_1 \tan_\phi / [\tan_1 + \tan_\phi] \]

Hence \( \tan_\tau G = \tan_1 \tan_\phi / [\tan_1 + \tan_\phi] \) \hspace{1cm} (6.30)

From equation 6.30 and knowing the truth of \( Q(G) \) is \( \tau_G \), the proposition \( G \) can be modified by \( TFM(G, \tau_G) \) to give the value of \( G' \) that is:

\[ \mu_{\tau G'}(z) = TFM(G, \tau_G) = \mu_{\tau G}(z) \tan_\tau G = z.\tan_\tau G.\tan_\tau G \] \hspace{1cm} (6.31)

Combining equations (6.25), (6.30) and (6.31) we have:

\[ \mu_{\tau G'}(z) = z.\tan_1.\tan_\phi \cdot \tan_\phi \tan_\phi \tan G / [\tan_\phi. \tan_1 + \tan_\phi. \tan_2] \] \hspace{1cm} (6.32)

Equation (6.32) can be used to calculate the function of proposition (g is \( G' \)).

As an example, we consider the following proposition:

IF the power output of the turbine is Very Good THEN the dependency of a building on the grid network is Very Little (VD - Very Dependent on the Turbine), this is True (TR)"
If it is True (TR) that the power output from the turbine is Fairly Good (FG), what is the conclusion?

The above proposition can be written as:

[Power output is Very Good (VG) ⊃ Somewhat Dependent on Turbine (ST)] is TR

[Power output is FG] is TR

\[ Q \text{ (performance is VG)} = \tan G \text{ and performance is } G' \]

Therefore we have \( \tan (ST) = \tan (TR) = \tan (\mu/4) \), \( \tan (VG) = \tan (3\mu/8) \) and \( \tan FG = \tan (\mu/8) \). Through the use of equations (6.25), (6.30) and (6.31) we have:

\[
\tan \tau_G = \frac{\tan (TR) \tan (FG) \tan (TR)}{[\tan (VG) \tan (TR) + (\tan (FG) \tan (TR))]}
\]

\[ = 0.146447 \]

And \( \tan (G') = \tan (ST) \tan \tau_G = 0.8996 \times \tan (ST) = 0.14677 \)

Hence \( G' \) is between fairly good \( \alpha = \mu/8 \) and Undecided \( \alpha = 0 \).

**6.3 Feasibility Test using Angular Model**

The equations above are used to develop the feasibility test in the C# program. The angular model can also give the user a negative or positive results based on the rules and facts chosen by the user.
The user would choose linguistic variables as a measure of power output and the dependency on the grid or the turbine. The linguistic variables for power output and the angles associated to them are:

- Exceptionally good = \( \pi/2 \)
- Very good = \( 3\pi/8 \)
- Good = \( \pi/4 \)
- Fairly good = \( \pi/8 \)
- Undecided = 0
- Fairly = \( -\pi/8 \)
- Poor = \( -\pi/4 \)
- Very poor = \( -3\pi/8 \)
- Exceptionally poor = \( -\pi/2 \)

The linguistic variables for dependency on the grid and the angles associated to them are:

- Not at all = \( \pi/2 \)
- Very dependent on the turbine = \( 3\pi/8 \)
- Somewhat dependent on the turbine = \( \pi/4 \)
- Fairly dependent on the turbine = \( \pi/8 \)
- I can’t say = 0
- Fairly dependent on the grid = \( -\pi/8 \)
- Somewhat dependent on the grid = \( -\pi/4 \)
Very dependent on the grid \[= - \frac{3\pi}{8}\]

Completely dependent on the grid \[= - \frac{\pi}{2}\]

### 6.3.1 How the Model Works

The user selects the rule, for example, the power output should be very good and the grid dependency should be fairly dependent. After selecting the rule, the user then selects a fact, for example, that the power is fairly good as shown in Figure 28.

![Angular model](image)

Figure 28: Angular model
Upon selecting the fact and clicking the calculate button the feasibility level is displayed, for this case the feasibility level is fairly feasible as shown in Figure 29.

![Feasibility Test (Angular Model)](image)

Figure 29: Angular model results page

### 6.4 Conclusions of the Angular Model

The angular model allows the user to select his/her own rules and facts. The linguistic variables in the angular model make it flexible and provide the user, who may not be aware of fuzzy logic, with a defuzzified answer. See Appendix B: Angular Model Program Images for additional images of results from this program.
CHAPTER 7: SUMMARY/RECOMMENDATIONS/CONCLUSION

7.1 Summary

Sustainable construction is a major challenge for today’s engineers. Meeting exceedingly high energy demands with limited resources of fossil fuels calls for the exploration of alternative energy resources. Global warming and rising CO₂ emissions into the atmosphere, and air pollution are also major concerns.

The construction and operation of commercial and residential buildings require immense amounts of energy and dependency on the conventional grid system. Alternative green sources of energy are a necessity for future building construction. Metric systems such as LEED and Green Globes have helped to influence sustainable construction and awareness in this new area of study.

The Intelligent Decision Making Tool (IDMT) developed in this research can help experienced and inexperienced engineers with the selection of small wind turbines at different locations in Ohio. The decision tree mechanism in this research obtained its parameters from experts in the industry and from the literature search. The turbines used in this research were similar to existing turbines available on the market, along with their costs and size. The IDMT not only recommends a suitable wind turbine but also calculates the payback period, LEED points earned, maintenance costs and an explanation facility explaining the logic used in an outcome.
The feasibility study implemented in the IDMT uses the angular model in which the user has the flexibility to select the rules and facts. A feasibility check is carried out by comparing the power output from the wind turbine with the expected dependency on the grid system upon installation of the wind turbine.

The IDMT can be used in locations other than Ohio, with the input of data for that location. For example, wind speed data for other locations would need to be gathered to obtain suitable results.

7.2 Conclusion

The IDMT would influence the use of renewable sources of energy on existing buildings. It would assist both experienced and inexperienced engineers in making decisions of installation of small wind turbines on buildings with different roof structures or tower installations. It is also essential that the user understands the logic used by the IDMT and its method of reasoning to arrive at a particular conclusion. The detailed results would provide the user with the ‘do’s and don’ts’ of installing a wind turbine, the possible LEED points that can be earned and the total costs associated with a turbine.

If the IDMT is improved as stated in the recommendations, then this approach could provide engineers with more accurate and reliable results in building and energy planning, thus increasing sustainability through the use of renewable wind energy.
7.3 Recommendation

The IDMT developed in this research is the first of its kind that helps determine the most suitable small wind turbine. For future studies and research on the IDMT, the following improvements are recommended to make the intelligent more effective and efficient.

Firstly, with the use of shells the IDMT can be developed into a knowledge-based expert system that would increase the capacity of the system to contain more data, have more rules, frames and parameters and function more efficiently to provide detailed results.

We used only nineteen wind turbines in this research; hence the user would only be recommended a turbine out of them. The small wind turbine market is a growing market with increasing demand, using more wind turbines with different rotor diameters, costs and type in the IDMT would increase the choices for the user and hence the effectiveness of the IDMT.

The wind speed data used in this research is attained from weather stations in Ohio. To increase the use and effectiveness of this system, additional wind speed data for other locations must be attained. This would increase the number of users that can use the IDMT.

The wind speed used in determining annual power output is an estimate wind speed taken, that is calculated by Davenport’s equation. To attain more accurate annual power output data from the wind turbines we should also consider surface roughness, wind turbulence and the weight and number of blades. More research needs to be done in this area that would provide us with better results of the effective wind speed in a particular location and eventually the effective power output from a wind turbine.
More research should be carried out on the effects on the roof slab upon the installation of a wind turbine. Wind loads and loads on the wind turbine would be taken into account to analyze the strength of a roof structure and its ability to support the wind turbine.

In this research, we study the effectiveness of a wind turbine on a building and aim to reduce the dependency of buildings on the conventional grid system. However, we do not entirely consider the life cycle of a wind turbine. To assess the carbon footprint imposed by the installation of a wind turbine we would need to include the extraction of raw materials used in the manufacture of turbines, its conversion into different components, manufacturing, commissioning and operating of the system, and its final disposal or recycle after use. When we use such systems, it is essential to account for the energy flow and emission potential of all phases of the project life. We would therefore need to analyze how green and sustainable the wind turbines are. We can work out the net energy analysis of a wind turbine to determine how sustainable it is by using the following equation (Sathyajith Mathew, 2006, 182–187)

\[ \text{EPR} = \frac{(E_A \times L)}{E_{CL}} \]

\[ \text{EPR} = \frac{(E_A \times L)}{E_{CL}} \]  \hspace{1cm} (7.1)

Where \( E_A \) is the annual energy production, \( L \) is the life period and \( E_{CL} \) is all the energy consumed during manufacturing, operation and disposal phases of the technology. For every turbine used in this research we can work \( E_A \) and \( L \); however it is very difficult to determine \( E_{CL} \), mainly because \( E_{CL} \) would vary for every turbine.
The above recommendations would allow the Intelligent Decision Making Tool to be more effective and provide more detailed results. These recommendations would make it easier to install the most suitable wind turbine at any location and calculate the expected power output. These updates would increase the influence on sustainable construction and the use of renewable sources of energy.
REFERENCES


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Hadipriono, Fabian C. and Sun, Keming. Angular fuzzy set models for linguistic values, 1990. Civil Engineering and Environmental Systems. 7 (3), 148-156


http://www1.eere.energy.gov/maps_data/pdfs/eere_databook.pdf


http://www.eia.doe.gov/electricity/
http://www.urbanwind.net/pdf/technological_analysis.pdf
APPENDIX A: INTELLIGENT DECISION MAKING TOOL (IDMT)

Figure 30: Intelligent Decision Making Tool 1
Figure 31: Intelligent Decision Making Tool 2

Figure 32: Intelligent Decision Making Tool 3
Figure 33: Intelligent Decision Making Tool 4
Figure 34: Intelligent Decision Making Tool 5

![Intelligent Decision Making Tool 5](image)

Figure 35: Intelligent Decision Making Tool 6

![Intelligent Decision Making Tool 6](image)
Figure 36: Intelligent Decision Making Tool 7
Figure 37: Intelligent Decision Making Tool 8

Figure 38: Intelligent Decision Making Tool 9
Figure 39: Intelligent Decision Making Tool 10
Figure 40: Angular Model Sample 1
Figure 41: Angular Model Sample 2

Figure 42: Angular Model Sample 3