IPRO It takes a team! INTERPROFESSIONAL PROJECTS PROGRAM

IPRO 303
Wind Power Generation:
Cost Impact of Equipment Failure
FINAL REPORT

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Date: Monday, December 8, 2008

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ADDENDA LIST

Addendum 1: **Questionnaire:** The list of questions that was prepared by the IPRO team to present to wind farm operators, wind turbine manufacturers and third party maintenance crews.

Addendum 2: **Contact List:** The list of wind industry contacts compiled during the semester. The format is a MS Excel spreadsheet.

Addendum 3: **Wind Farm Visit:** A summary of notes from a wind farm visit that the team made during the semester.

Addendum 4: **College Interview Summary and Notes:** Notes from an interview with a representative from local college that operates a small scale wind turbine.

Addendum 5: **Wind Turbine Component Failure Economic Impact Calculator:** This workbook calculates the economic cost of specific faults on a single wind turbine.

Addendum 6: **Calculator for Wind Farm Income and Costs:** This workbook is intended to give insights into the revenues and costs associated with owning and operating a wind farm that has multiple turbines.

1. Abstract

The Fall 2008 semester of IPRO 303 was focused on determining the cost impact of equipment failure in large scale wind farms. This information was gathered for the purpose of creating a technical business case for the project sponsor, SmartSignal Inc. The group was divided into various teams as the semester progressed. Initial research was carried out to learn about the wind power industry and the role it played in the overall energy market. At the same time, research into the mechanics of wind turbines was done and common equipment failures were classified. The cost associated with downtime and maintenance of wind turbines was analyzed and attempts were made to determine current industry practices in dealing with these problems. This was done by doing library & web research, and directly contacting the various parties involved, including wind farm operators and turbine manufacturers. Finally, a technical business case was created in the form of an interactive spreadsheet. This spreadsheet was developed to allow the sponsor to input a scenario particular to the wind power industry and receive a detailed economic analysis of the true costs that would be involved. The information could then be used by the sponsor to demonstrate to potential customers the benefits of employing their services.

2. Background

A. **Sponsor Information:** SmartSignal Inc. offers software which models machine and equipment behavior, and can learn to distinguish between normal and abnormal conditions. This information is used by machine operators to proactively deal with potential problems before they cause faults and unplanned downtime. It can also be used to determine when preventive maintenance is actually needed, which can reduce costs by limiting unnecessary maintenance. SmartSignal has a long history of providing its products and services to many different industries. It does not currently deal with the wind power industry, but views this area as a potential future market for its products. Developing this market will require an in-depth understanding of the nature of equipment failures and industry maintenance practices, including all economic costs. An accurate awareness of the true costs of faults, planned and unplanned down-time, and maintenance and repair practices is therefore important to understanding the role SmartSignal's products can play in this industry. Equally important is an understanding of the accuracy of current industry perceptions of these costs. The main focus of IPRO 303 for this semester was therefore to research the wind energy sector and aid SmartSignal in determining its future role in this market. This was done by meeting three main objectives provided by the sponsor. The objectives are given in section 3 of the report.

B. **Addressed Problems:** As indicated in the paragraph above about SmartSignal, the intention of IPRO 303 was not to solve an existing problem but to help the sponsor gain a better understanding of the current maintenance paradigm that exists in the wind-turbine power generation industry.

C. **Technology Involved:** Technical report writing and computational analysis software was employed in analyzing the data and information collected. MS Excel software was used to sort the data and to perform the calculations that were carried out. The results were also reported in the form of spreadsheets and graphs outlining important findings. Email was used extensively to contact industry representatives and also for team member communication. The internet was also used for research and to find contact information. MS PowerPoint software was used to create presentations as part of the IPRO deliverables and also for meetings with the sponsor to visually communicate progress reports. Telephone conference calls were used to communicate with the sponsor when it was not possible for an in-person visit. Remote Desktop software was used by the sponsor to control slides in the presentation during the conference call meeting.

D. **Ethical Issues:** SmartSignal operates in a competitive market and it was ensured that any classified or sensitive information or document obtained from SmartSignal was kept confidential and was not disclosed to anyone outside the project team. SmartSignal also requested at the beginning of the project that we not mention their sponsorship of IPRO 303's project when gathering information. This issue was reviewed during a mid-term meeting with SmartSignal and it was decided that any information gathered from other companies would also be kept anonymous to SmartSignal.

3. Objectives

The initial objectives of the IPRO are listed below, as provided by the project sponsor. Each objective was approached simultaneously by specific teams that were formed for that purpose, in order to save time:

A. Explain faults that are occurring in wind turbines and why: The team was to gain a general understanding of how wind turbines work and to identify the major turbine components. The major failures associated with those components were to be determined as well. Next, the most costly or most common reasons for turbine downtime were to be found and classified. This research was done by using resources such as the library, the internet and also wind-industry data provided by the project sponsor.

B. Provide overview of current maintenance practices and procedures: The team was to provide listings of maintenance procedures available in the industry and determine the advantages and disadvantages of current maintenance practices. The team was also charged with finding out who was responsible for maintenance in wind farms i.e. the turbine manufacturers themselves or 3rd party maintenance companies. In order to meet this objective, the team had to establish contacts in the industry and interview them for the necessary information.

C. Cost Analysis: One of the teams' objectives this semester was to create a detailed cost analysis to describe the revenues and cost basis of wind power generation. This analysis illustrated how various factors associated with wind power generation affect the cost of energy (COE) produced. Our team focused on operations and maintenance (O&M) and how the alteration of this factor either increased or decreased the cost of energy produced. This cost analysis was created in the form of a Microsoft spreadsheet calculator which accepts variables from the user and simulates a COE value.

4. Methodology

The methodology of the project was changed slightly from the beginning of the project to include what was actually done. Tasks may not have been carried out in the same order, but the listed goals were definitely accomplished even though optimal due process may not have been followed:

A. **Defining the problems:** The cost of failures associated with wind turbine operations was determined. This was important because it aided in developing preventative turbine failure measures:

- Understand wind turbine failure modes and their causes.
- Understand the current paradigm for maintenance practices.
- Cost analysis of wind turbine downtime

B. **Gathering research:** Research and background information on turbine failures was gathered:

- Available wind data resources were used to do this
- Wind turbine manufacturers, operators, and 3rd party maintenance crews were contacted with questions regarding turbine faults that occur, staffing expertise, organizational arrangements of maintenance programs etc.
- The team determined what maintenance was performed in-house and what was "farmed out" by wind farm operators.
- Some warranty issues with turbine manufacturers were looked into.
- The kind of technology and tools used to combat turbine downtime were determined.

C. **Initial data compilation and feedback:** Compilation of results gathered from research over the semester:

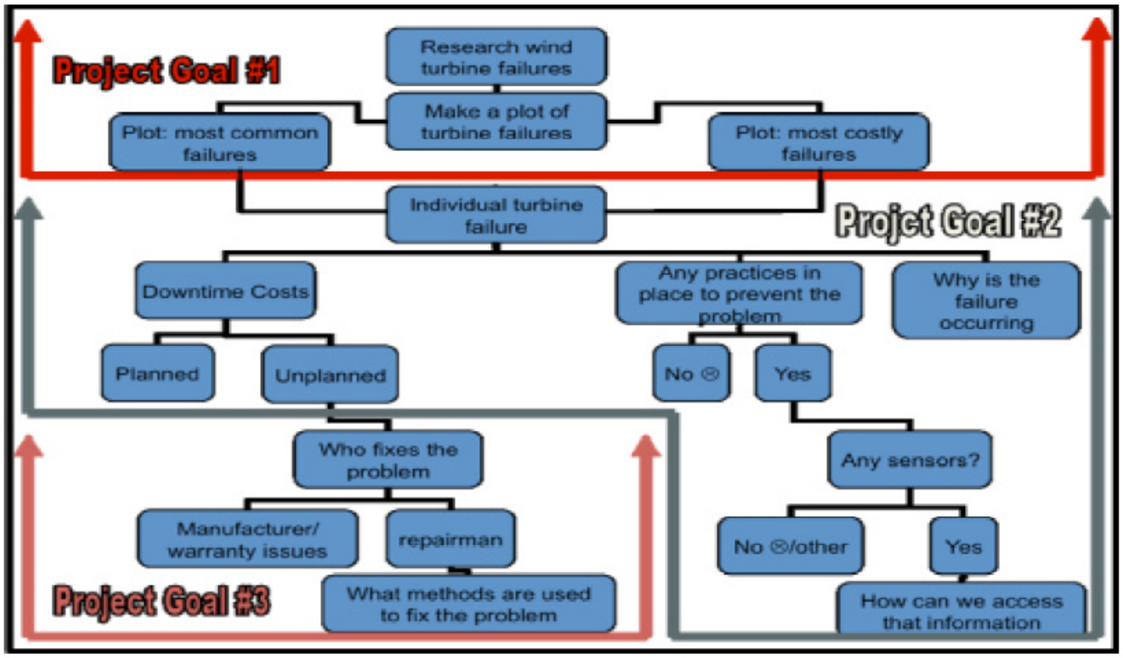
- Information received was put together in a report which served as the midterm report and doubled as a team progress report.
- The sponsor was contacted to provide feedback as to the direction the project had been going and where it was headed.

D. **Prepare Cost Analysis:** Compiled data was used to prepare a cost analysis in the form of a MS Excel spreadsheet:

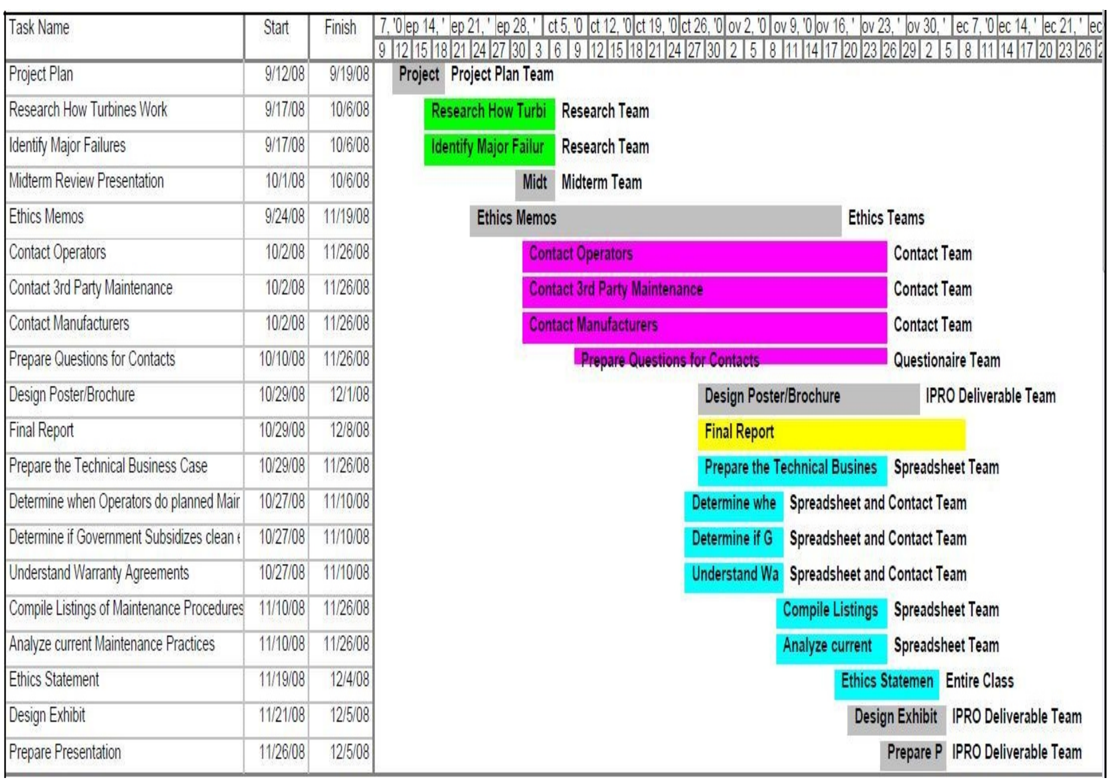
- The cost analysis included costs and comparison of unplanned downtime (due to failure) and planned down time (in other words, scheduled maintenance).
- It also included the methods that are used to fix the problems.
- The spreadsheet was comprehensive and allowed for the simulation of various scenarios to give outputs of cost in terms of monetary value.

E. IPRO Day: As the project did not produce a working prototype, the results of the semester were exhibited using graphs, charts and spreadsheets. The project goals and conclusions were included in the final presentations and exhibit.

F. Work Breakdown Structure: The Breakdown Structure of the work that was done by the group is given in the flow chart below:



G. Gantt Chart: The Gantt chart for the second half of the semester is given below. The chart is a continuation from the mid-term progress presentation and includes tasks and teams formed up until the final IPRO day:



Task Name	Start	Finish
Project Plan	9/12/08	9/19/08
Research How Turbines Work	9/17/08	10/6/08
Identify Major Failures	9/17/08	10/6/08
Midterm Review Presentation	10/1/08	10/6/08
Ethics Memos	9/24/08	11/19/08
Contact Operators	10/2/08	11/26/08
Contact 3rd Party Maintenance	10/2/08	11/26/08
Contact Manufacturers	10/2/08	11/26/08
Prepare Questions for Contacts	10/10/08	11/26/08
Design Poster/Brochure	10/29/08	12/1/08
Final Report	10/29/08	12/8/08
Prepare the Technical Business Case	10/29/08	11/26/08
Determine when Operators do planned Mair	10/27/08	11/10/08
Determine if Government Subsidizes clean (	10/27/08	11/10/08
Understand Warranty Agreements	10/27/08	11/10/08
Compile Listings of Maintenance Procedures	11/10/08	11/26/08
Analyze current Maintenance Practices	11/10/08	11/26/08
Ethics Statement	11/19/08	12/4/08
Design Exhibit	11/21/08	12/5/08
Prepare Presentation	11/26/08	12/5/08

5. Team Structure and Assignments

The initial structure of the team was changed after a mid-term course correction. This occurred after a visit by the sponsor representative and required new teams to be created. The following table gives an overview of the respective disciplines of team members along with individual skills and strengths:

Name	Major and Year/level	Skills and Strengths	Experience and Academic Interests
Chris Catalina	MSE - Materials Science and Engineering / ME - Mechanical Engineering 4th year	Strengths: Thorough, Work well with others. Computer skills: AutoCAD, Pro-Engineer, MATLAB, MS office, C++	-Familiar with mechanical testing of materials, knowledge of basic heat treating principals. -Interest in materials processing as well as alternative energy.
Laolu Adeola	MAE - Mechanical and Aerospace Engineering / Business Administration 3rd year	Strengths: Working with people/teams Computer skills: Mac, PC, Linux, Microsoft Office, Illustrator, MATLAB, Maple, C++, AutoCAD	-Entrepreneurship
Viral Patel	AE - Aerospace Engineering / ME - Mechanical Engineering 4th year	Strengths: Punctual Computer skills: MS Office, MATLAB, Pro/Engineer	-Interested in aerodynamics of wind turbines
Don Ruffatto	ME Mechanical Engineering 4th year	Strengths: Data analysis, interpretation, problem solving. Computer skills: MS Office, MATLAB, Pro/Engineer, Autodesk Inventor.	-Researched wind turbines for a previous IPRO -Industry experience in automation -Interested in mechanical design and automation.
Sara Claxton	AE - Aerospace Engineering / ME - Mechanical Engineering 4th year	Strengths: Graphic design Computer skills: MS Office, DA DISP, Pro/E, AUTOCAD.	-Interned at a government company (Internal Ballistic Actuation). -Interested in aerodynamics and blended wing design.
Earl Fairall	AE - Aerospace Engineering 4th year	Strengths: Technical project leader/coordinator. Computer skills: Solidworks	-Interested in mechanical design -Technical Background in electric motors and mechanical systems
Mithun Michael	EE - Electrical Engineering 4th year	Strengths: creative, hard working, task oriented Computer skills: MS Office, MATLAB/SIMULINK, PowerSim, PSpice, C++/JAVA	-Interested in grid integration of wind turbines/intelligent control of power systems -Interested in renewable energy technology
Jesus Cervantes	ME - Mechanical Engineering 4th year	Strengths: Fixing/Drawing Computer skills: MS Word	-Interested in automobiles
Samad Erogbogbo	ME - Mechanical Engineering 4th year	Strengths: analytic, problem solving, team projects. Computer skills: MS Word	-Previous IPRO, -Intern in automotive engineering industry
Rob Keane	EE - Electrical Engineering 4th year	Strengths: Experience. Computer skills: programming	-Electrical and Electronics Engineering
Kristina Lakiotis	CS - Computer Science 4th year	Strengths: Graphic design Computer skills: Programming, graphic programs.	-Interested in alternative energy
Richard Ike	ME - Mechanical Engineering 4th year	Strengths: Organization, Problem solving Computer skills: AutoCAD, Pro/E, MATLAB, MS office	-Metallurgical and Mechanical Testing
Aaron Melko	AM - Applied Mathematics / AE - Aerospace Engineering 4th year	Strengths: Data analysis, organization Computer skills: Word, Excel, AutoCAD	-Mathematics -Teaching, Mentoring

A. Initial Assignments: The initial teams created at the beginning of the semester are given in the table below, along with a brief description of the team responsibilities:

Research 1	Contact Team	Research 2	Ethics
Jesus Cervantes	Laolu Adeola	Sara Claxton	Kristina Lakiotis
Samad Erogbogbo	Chris Catalina	Earl Fairall	Rob Keane
Rob Keane	Richard Ike	Aaron Melko	-
Kristina Lakiotis	-	Viral Patel	-
Mithun Michael	-	Donald Ruffatto	-

Research 1: This sub group was involved in researching how wind turbines work and identifying the major failures that this IPRO team focused on.

Research 2: This sub group was in charge of preparing questionnaires for the contact team.

Contact: The contact team was responsible for contacting operators, 3rd party maintenance, and manufacturers to schedule interviews.

Ethics Team: The ethics team considered and analyzed the important ethical consequences of the request by our sponsor to keep their name out of any correspondence with other companies.

B. Team Leaders: Team leaders were assigned after the mid-term presentation. Earl Fairall and Donald Ruffato were appointed as co-team leaders. The leaders were chosen after a lengthy team discussion and a final vote. The primary tasks of the team leaders were to assign sub teams and ensure that all tasks were equally distributed. The team leaders also reminded members of deadlines, coordinated meetings and outlined meeting agendas.

C. Revised Assignments/Teams: The group was restructured into three distinct teams after the mid-term progress presentation. The new teams and members are given in the table below:

Spreadsheet Team	Contact Team	Deliverables Team
Jesus Cervantes	Chris Catalina	Laolu Adeola
Samad Erogbogbo	Mithun Michael	Sara Claxton
Richard Ike	-	Samad Erogbogbo
Rob Keane	-	Kristina Lakiotis
Aaron Melko	-	Viral Patel

Spreadsheet Team: This team was created to analyze and compile all data pertaining to wind turbine failures and costs associated with down-time. The team created a spreadsheet in the form of a final deliverable for the project sponsor. This spreadsheet contained in detail, the cost of failure of individual components, possible loss of government tax incentives for wind farm operators, the costs of crane rental and lost production time etc. The spreadsheet was also made as an interactive program that expected user input of possible scenarios and output total associated costs.

Contact Team: This team was unchanged although some of the original members were reassigned to other teams. As before, the responsibility of the contact team was to get in touch with industry professionals and attempt to gather information through phone interviews. The team also utilized the questionnaire that was previously created to survey the people that were contacted. Finally, the contact team arranged for and organized a visit to a local wind farm.

Deliverables Team: The deliverables team was in charge of preparing all the final documentation for the IPRO and creating the poster and brochures for the IPRO day exhibit. In addition, the team created the final presentation and consolidated all electronic documents for final submittal to the IPRO office and the project sponsor.

D. Meeting Minutes: Meeting minutes were taken by each team member on a rotating basis. The schedule of minute takers was created at the beginning of the semester and minutes were uploaded and corrected after each meeting.

6. Budget

The budget was revised as the semester progressed and actual expenses were accounted for as they were incurred. A summary is given in the table below:

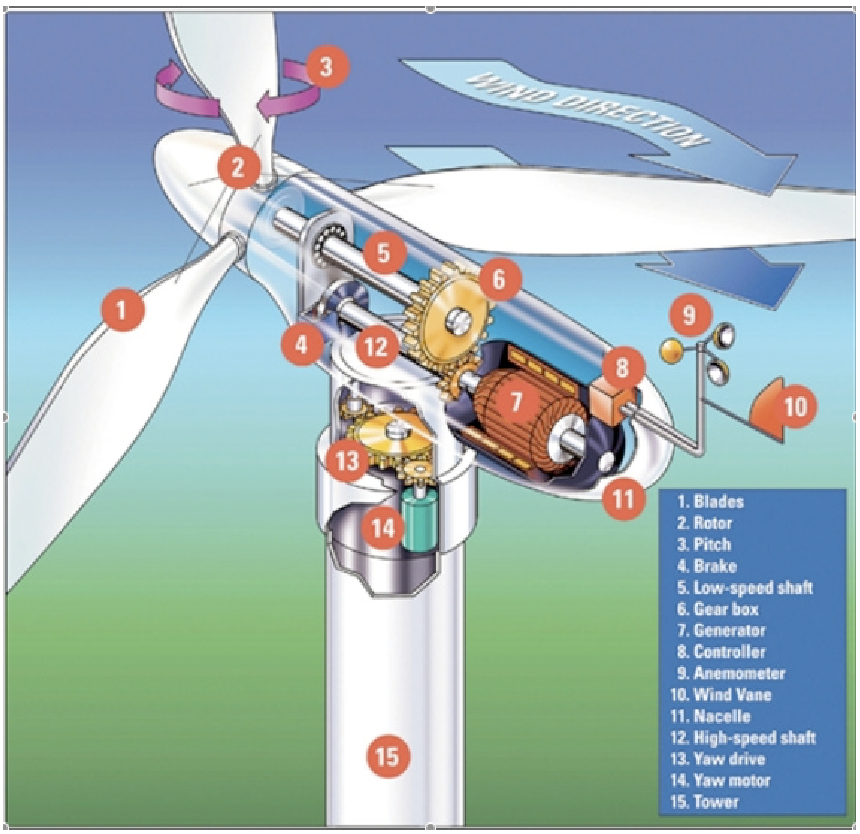
Expense	Allotted amount	Actual amount	Notes
IPRO Day	$100	$0	Presentation board, handouts, supplies
Miscellaneous	$150	$28.93	Food for extended team meeting
Transportation	$500	$223.45	Wind farm visit/Travel Expenses
TOTALS	$750	$252.38	
		$497.62	Amount under budget

7. Results

The initial IPRO objectives were completed according to the requirements of the sponsor. These were classified in the beginning of the report. The results are stated below in the same order as the objectives:

A. EXPLAIN FAULTS THAT ARE OCCURRING IN WIND TURBINES AND WHY:

Identify turbine components: The basic components of a turbine depend on the size and capacity of the turbine. The schematic below highlights the main components:



Source: Alliant Energy Kids http://www.alliantenergykids.com

As mentioned above, all turbines do not have the same components. However, they generally include the following [1] [2]:

- Tower
- Rotor
- High and low speed shafts
- Mechanical gearbox

• Electric Generator
• Yaw mechanism
• Sensors and Control
• Sensors to monitor and regulate various electrical and mechanical parameters
• Anemometers to measure and transmit wind speed data to controller
• Stall controller to shut down the system at excessive speeds to percent blade overstressing or generator overheating.
• Power electronics converters to condition power output to the required standards
• Control electronics
• Battery pack to allow stand alone operation if necessary
• Transmission link to connect to area grid.

Gain a general understanding of how wind turbines work: The operation of a large scale wind turbine is fairly complex. Listed below is the terminology used to describe various components and their functions:

• Low speed shaft: the turbine rotor runs this shaft (usually 30-60rpm)
• High speed shaft: this shaft drives the generator via a step up gear.
• Brake: Stops the rotor in an emergency. (can be applied mechanically, hydraulically or electrically)
• Gearbox: gears connect the low speed shaft to the high speed shaft and help increase turbine speed (30-50 rpm to 1000-1800 rpm), as required by the generator for efficient generation of electricity.
• Nacelle: it sits on top of the tower and includes the gearbox, high and low speed shafts, generator, controller, and mechanical break system.
• Pitch: Blades are turned out of the way of the wind direction when wind speeds are too high or too low for optimal functioning. Pitch control involves changing the pitch of the blade in accordance with wind speed to regulate rotor speed.
• Upwind /Downwind types: The upwind turbine operates facing into the wind in front of the tower, whereas the downwind runs facing away from the wind behind the tower.
• Yaw Drive: Its function is to orient the turbine in the direction of the prevailing wind. A yaw motor powers the drive mechanism.
• Vane: Its function is to measure the wind direction and communicate to the yaw mechanism so as to orient the turbine properly in the direction of the wind

During normal operation, changes in wind speed and direction are taken care of by two control systems. The Yaw is controlled by a Yaw control unit that keeps the turbine facing into the wind. It allows the turbine to position itself to face the direction that maximizes lift on the blades. There is the possibility of the yawing cable mechanism inside the tower to get twisted if by accident the turbine kept yawing continuously in one direction. The turbine is therefore equipped with a cable twist counter that instructs the controller to untwist the cables as required. Pitch (blade angle) is controlled by the pitch controller. A sudden change in wind speed will be compensated for by a change in pitch. The angle of attack of the blades is adjusted which will then adjust speed of rotation as required by the generator for the correct power output.

Classification of wind turbines: Wind turbines are generally classified according to the axial positioning and the power capacity.

I. Axial Position: Axial position of the turbine refers to the axis about which the turbine blades rotate. The different types of axial position turbines are [1] [2]:

Horizontal Axis wind turbines (HAWT): Horizontal axis wind turbines are the most common type. It makes use of blades with a horizontal axis of rotation and is the easiest way to convert wind's linear energy into rotational one. Under steady state conditions each blade section experiences a constant angle of attack during one revolution. (The angle of attack is the angle between the direction of wind flow and the direction of a line drawn parallel to the blade). Therefore, it is extremely important that the wind turbine yaws (or turns) to maintain alignment with the direction of the wind. Also, by turning the face of the blade away from or into the wind, the lift on the blade (and thereby the velocity of the blade) can be increased or decreased.

Vertical axis wind turbines (VAWT): These use blades with a vertical axis of rotation. Therefore, the angle of attack experienced by each blade varies continuously through one revolution. The advantage here is that he VAWT has no need to yaw with changing wind directions, and can operate in regions with variable wind speeds effectively.

Advantages/Disadvantages of HAWT's and VAWT's (Excerpt from Wikipedia) [Source: http://en.wikipedia.org/wiki/Wind_turbine]

"HAWT advantages [3]:

1.) Variable blade pitch, which gives the turbine blades the optimum angle of attack. Allowing the angle of attack to be remotely adjusted gives greater control, so the turbine collects the maximum amount of wind energy for the time of day and season.

2.) The tall tower base allows access to stronger wind in sites with wind shear. In some wind shear sites, every ten meters up, the wind speed can increase by 20% and the power output by 34%.

HAWT disadvantages:

1.) HAWTs have difficulty operating in near ground, turbulent winds.

2.) The tall towers and blades up to 90 meters long are difficult to transport. Transportation can now cost 20% of equipment costs.

3.) Tall HAWTs are difficult to install, needing very tall and expensive cranes and skilled operators.

4.) Massive tower construction is required to support the heavy blades, gearbox, and generator.

5.) Tall HAWTs may affect airport radar.

6.) Their height makes them obtrusively visible across large areas, disrupting the appearance of the landscape and sometimes creating local opposition.

7.) HAWTs require an additional yaw control mechanism to turn the blades toward the wind.

VAWT advantages:

1.) No massive tower structure is needed.

2.) As the rotor blades are vertical, no yaw mechanism is needed.

3.) A VAWT can be located nearer the ground, making it easier to maintain the moving parts. Also, being situated close to the ground can be advantageous in locations where mesas, hilltops, ridgelines, and passes funnel the wind and increase wind velocity.

4.) Straight bladed VAWT designs with a square or rectangular cross-section have a larger swept area for a given diameter than the circular swept area of HAWTs.

5.) VAWTs have lower wind startup speeds than HAWTs.

6.) VAWTs do not need to turn to face the wind if the wind direction changes.

7.) VAWT blades are easily seen and avoided by birds.

VAWT disadvantages:

1.) Most VAWTs produce energy at only 50% of the efficiency of HAWTs in large part because of the additional drag that they have as their blades rotate into the wind.

2.) VAWTs do not take advantage of the stronger wind at higher elevation.

3.) Most VAWTs have low starting torque, and may require energy to start the turning.

4.) While VAWTs' parts are located on the ground; they are also located under the weight of the structure above it, which can make changing out parts near impossible without dismantling the structure if not designed properly."

II. Power Capacity: Other criterion for wind turbines is based on their installed power capacity, classified below:

Small wind turbines: These are of generally up to 20 kW power. In 2001, an annual sale of the U.S. Small Wind Turbine Industry was estimated to be 13,400 turbines valued at about $20 million. It is projected that small wind turbines could contribute 3% of U.S. electrical consumption by 2020 [4]. Small wind turbines are used for home applications, supplying households with electricity, and they are designed for small cut in wind speeds (generally 3-4m/s). They are also suitable for remote places where grid is far away and power transmission is difficult. Small wind generators can operate as isolated power systems for households' loads, and are usually connected to batteries. The figure below shows a small wind turbine in operation:

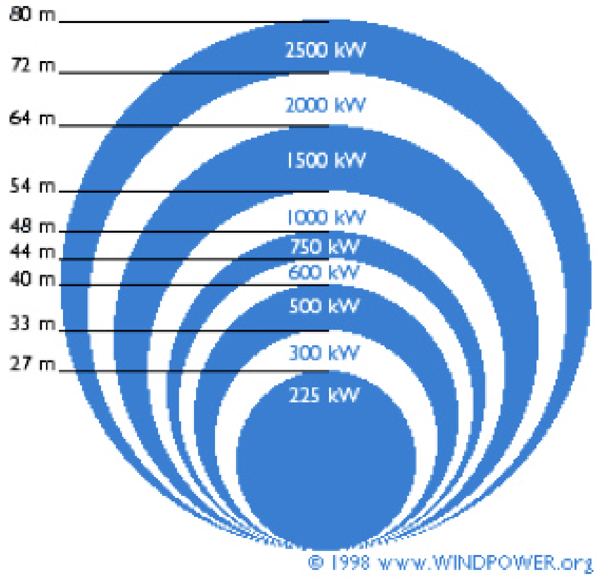
Source: http://www.northfultontimes.com/

Medium wind turbines: These usually provide between 20kW and 300kW of installed power. They are used to supply either remote loads that need more electrical power or commercial buildings, where small turbines are not powerful enough. Medium wind turbines have a blade diameter of 7-20m long, and the tower is not higher than 40m.

Large wind turbines: Large turbines are in the MW power range. These are complex systems and are usually a part of wind farms which consist of several hundred of these large turbines. The figure shows one of the world's biggest wind turbines (as of November 2007) located in Emden, Germany:

Source: Enercon, German Wind Turbine Manufacturer http://www.enercon.com

The turbine was built by the German company Enercon. The model is E-126, and has a power output of 6 Megawatts with a rotor blade diameter of 127 meters, hub height of 135 m and is capable of producing 20 million kWh of energy per annum, enough for powering 5000 4-person households with clean energy. It is important to note that power output increases with the swept rotor area. This is illustrated in the schematic below:



Source: Danish Wind Power Association http://www.windpower.org

Due to the increase in size, the price per installed kW of power of large wind turbines is much less compared to small turbines. This makes them more economical in the long run.

Determine wind turbine faults: Wind turbine components that usually fail vary amongst different wind farms. This is because these wind farms are subject to different weather conditions, size of turbine, make, and model of turbine. Though it is very difficult to determine a source of information that accurately lists turbine faults for all wind turbines, an example can be taken from wind farms in a certain region. An example of typical parts that fail is taken from a case study on wind turbine component failures conducted in Sweden. These include wind farms in Germany and Sweden. The following is a list created by this case study [4] and demonstrates the failure frequency per component.

Major Faults	
Electrical System	17.5%
Sensors	14.1%
Control System	12.9%
Blade Pitch	13.4%
Contribution ~ 60%	

Although these components have a higher failure frequency than other components of a wind turbine, these do not contribute the most to wind turbine downtime. Usually these components require repairs that do not require the use of a crane (except blade replacement) and can be fixed up tower. Also, these types of repairs do not require long stoppage hours associated with crane mobilization. The use of a crane can take days because many times the crane is located off the site of a wind farm. Using a lattice boom crawler crane adds to the downtime because these require assembly and disassembly of the crane along with a great amount of manpower. The following is a list created by the Sweden case study [4] and demonstrates the amount of downtime:

Most Downtimes	
Gears	19.4%
Control System	18.3%
Electric System	14.3%
Yaw System	13.3%
Contribution ~ 65%	

It can be observed that the gearbox contributes the most in terms of downtime, followed by the control system and the electric system.

<u>Determine most costly/most common reasons for turbine downtime</u>: Gearbox failures are the most costly component that affects turbine downtime. The gearbox bearing and gear are the main reason that this component fails. This is mainly caused by contamination and lack of maintenance [5]. Contamination can be caused from initial manufacturing of the gearbox (lack of cleanliness, contaminated oil, dust particles), internal generation (wear and tear particles from meshing of gears), through breathers or seals (air, water, foreign debris), and accidentally through maintenance (opening of the gearbox, removal of oil dipstick, etc. are pathways for debris to get in) [6]. A lack of maintenance is usually caused by a lack of regular oil changes. Regular oil changes are needed to prevent the gearbox components from developing sludge and to wash away metal particles developed from the meshing of the gears. Turbine operators may choose not to have maintenance inspections regularly. There are several reasons this may not occur. There may not be a qualified technician available in the area, or they are not able to afford it, having to spend their funds on repairing faults that have already occurred. To prevent a lack of lubrication, oil-monitoring systems are available to help operators know when to change the oil [7]. The typical costs associated with gearbox repair are [8]:

- Replacing a gearbox can cost around $120,000 for a 660 kW turbine.
- This includes local crane service if the crane is already on site
- A rebuild can cost around $40,000-$50,000 for the same type.
- Higher producing power wind turbines are more expensive.
- If a lattice boom crawler crane is required, total crane costs can reach $50,000-$70,000 alone*.

* This figure is somewhat inconsistent with other sources. A total of $300,000 for crane costs was found from one source.

<u>Environmental conditions that affect wind turbines</u>: Commercial scale wind turbines are generally designed to function between -20^{o}C and 40^{o}C. Some have weather packages to protect against extreme temperatures such as component heating and cooling. These packages include heated anemometers, black blades that absorb solar energy and prevent icing, and blade heating systems. Wind turbine faults due to extreme temperatures are listed below [9]:

<u>Cold Climates</u>:

1.) Extreme Temps: Many turbines are designed to stop when temperatures are exceeded. Increased density of air at cold temps can cause power output to exceed rated power and create increased loads on turbine. Overcurrent, overspeed, or other electrical faults may occur from this.

2.) Icing: The areas that experience cold temperatures and high humidity are most likely to ice. Icing increases loads on rotor blades and can lead to blade damage.

3.) Lightning: Midwest, northeast, and Southwest region of the U.S experience significant lightning activity. The size of the wind turbine is proportional to increase in lightning risk. Lightning strikes can cause small fuse failures and blade damage. Static electricity and nearby ground strikes can cause damage to susceptible electrical components.

4.) Hail: Midwestern plains and southern regions of the U.S are prone to large hailstorms. Damage to rotor blades can result from this. Hailstorms can occur with little warning.

<u>Hot Climates</u>:

1.) At hotter temperatures, the density of air is lower and affects wind turbines by not providing a sufficient amount air to generate a reasonable amount of power.

B. PROVIDE OVERVIEW OF CURRENT MAINTENANCE PRACTICES AND PROCEDURES:

Types of maintenance: Maintenance practices can be divided into two categories, scheduled and unscheduled maintenance. Scheduled maintenances are typically used as preventative measures to ensure the reliability of turbine components, while unscheduled maintenances generally come after a problem has been detected, either through inspections or monitoring systems.

Preventative Maintenance: Preventative maintenance is performed periodically and is typically scheduled ahead of time. "The objective of preventive maintenance is to replace components and refurbish systems that have defined useful lives, usually much shorter than the projected life of the turbine. Tasks associated with scheduled maintenance fall into this category and include periodic inspections of the equipment, oil and filter changes, calibration and adjustment of sensors and actuators, and replacement of consumables such as brake pads and seals. Housekeeping and blade cleaning generally fall into this category. The specific tasks and their frequency are usually explicitly defined in the maintenance manuals supplied by the turbine manufacturer. Costs associated with planned maintenance can be estimated with reasonable accuracy, but can vary with local labor costs and the location and accessibility of the site. Scheduled maintenance costs are also dependent on the type and cost of consumables used." [Sandia 10]

Unscheduled Maintenance: "A certain amount of unscheduled maintenance must be anticipated with any project. Commercial wind turbines contain a variety of complex systems that must all function correctly for the turbine to perform; rarely are redundant components or systems incorporated. Failure or malfunction of a minor component will frequently shut down the turbine and require the attention of maintenance personnel." [Sandia 10]

Typical Maintenance Procedures: "The relative scale of large wind turbines poses difficulty in accessing and working on the components. With the exception of some switchgear and power conversion equipment, most the turbine equipment is accessed by climbing the tower. For safety reasons, a two-person crew is generally required for any up-tower activity. In remote locations, access to the turbine itself may be difficult and limited by weather. Working conditions can be in extreme temperature conditions and may be curtailed by high winds. Some turbines are equipped with hoists and rigging equipment, but in general, all tools and equipment, in addition to spares, must be lifted into the nacelle. Space is limited inside the nacelle and working positions may be awkward. Work outside of the nacelle, including transitions into the hub on some turbines, requires working with a safety harness and lanyards.

Replacing Components: Although some major components may be reworked inside the nacelle, this is not generally the case, and replacement will require a crane to dismantle the drive train, and several personnel in addition to the crane operator. The equipment and procedures for disassembling the rotor or drive train are established during assembly. The cost associated with dismantling a wind turbine may vary due to accessibility to the turbine site, equipment availability, and wait time during high-wind conditions. The availability of cranes capable of lifting turbine components in the MW capacity range is limited in many of the remote locations where wind farms are being developed, and mobilization costs alone can make up a major portion of the repair cost.

Labor: Labor for minor repairs (those associated with sensors, actuators or control components that fail or function intermittently) is generally accounted for by assigning a number of turbines to each technician. Due to the difficulty in accessing the equipment, travel and climbing time may be much higher than the actual time required to diagnose and repair individual components, and intermittent malfunctions that are difficult to diagnose may require multiple trips." [Sandia 10]

Maintenance Contract Options: When a wind farm operator purchases a wind turbine, he has the option of purchasing a warranty from the turbine manufacturer, electing to contract a third party maintenance crew, or handling all maintenance and repairs with his own equipment on site. The correct option to choose varies for different operators and site locations, as well as the overall scale of a particular wind farm.

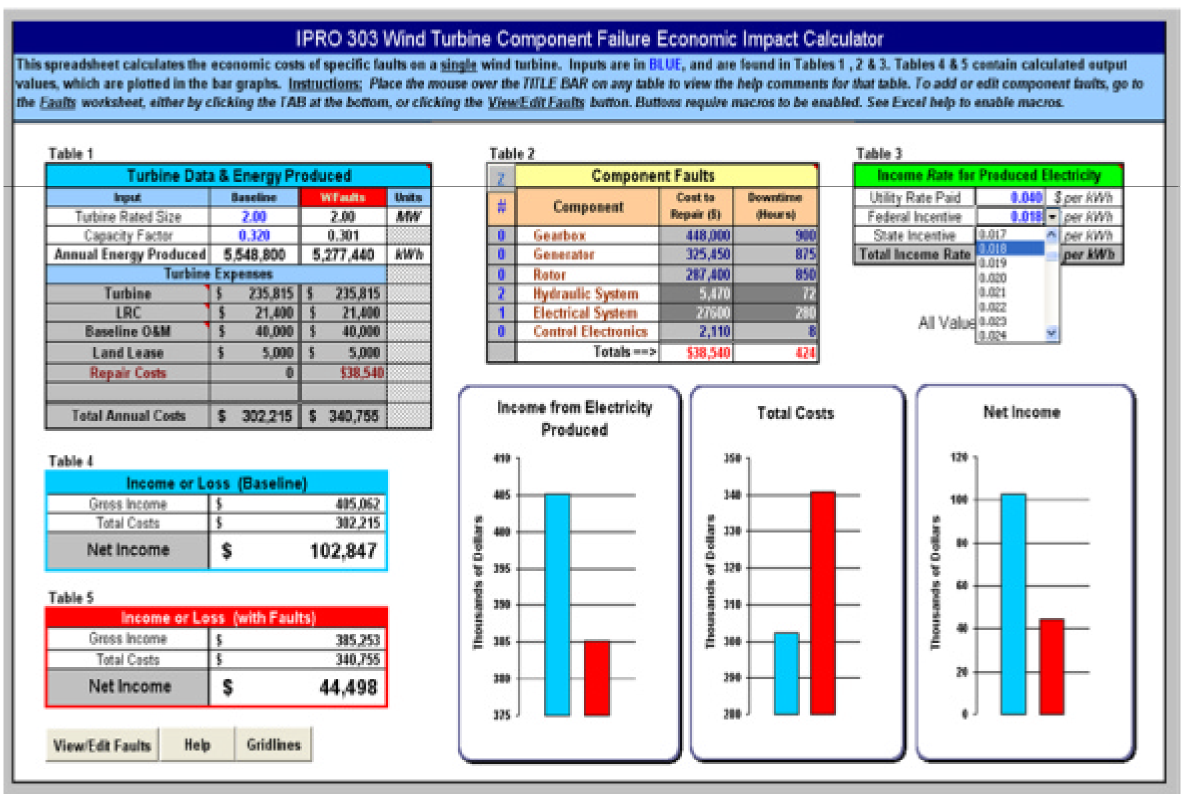
Manufacturer Warranty: Wind turbine manufacturers typically offer warranty options to their customers. The warranty can vary from covering just the failed components to complete coverage that deems the manufacturer fiscally responsible for all turbine failure issues. In the case when the warranty only covers parts, the operator is responsible for all repair and downtime costs, including crane rental, labor costs, lost revenue due to downtime, etc. On the other hand, a warranty agreement can hold the manufacturer liable for all turbine maintenance. Coverage might also include compensation for lost revenue during the repair. As part of the warranty agreement with full coverage, a manufacturer may choose to not share maintenance and monitoring logs with the operator. These logs can also include any sensor readouts that might have lead to a particular turbine fault and are valuable for understanding the operation of the turbine.

3rd Party Maintenance Crews: An operator that is not under a complete warranty with a manufacturer may choose to employ third-party maintenance crews. Crews can be hired to repair faults as they occur, or they can be contracted to particular wind farms. Depending on the scale of a particular wind farm, an operator can choose to have on-staff maintenance crews rather than hire a third-party company to handle repairs, where the only difference between the two options is which person or company is liable for repairs or other unseen problems.

C COST ANALYSIS WORKBOOKS:

<u>**Spreadsheet:**</u> The cost analysis was made in the form of two main workbooks that allow user input. A number of scenarios can be created by allowing the user to specify a certain failure or failures. The spreadsheet then calculates and outputs the associated costs resulting from the turbine downtime. Working versions of the workbook are attached to the report as addenda 5 and 6.

Wind Turbine Component Failure Economic Impact Calculator: This workbook was created to determine the cost analysis of various faults on a single wind turbine. The user is asked to choose turbine parameters, electricity rates and component faults. This is done by selecting options from drop-down lists which are user-editable. The economic effects of faults are then compared to the baseline. A screenshot of the main page from the workbook is given below:



The second sheet from the workbook deals with specific faults in the wind turbine. The default sheet contains six common faults. The downtime, labor rates, equipment rental rates, and spare part costs are entered by the user. The spreadsheet then calculates total costs and down-time associated with each fault and populates a table. This table (table 2 in the main spreadsheet) is then used to calculate outputs. A screenshot of the faults spreadsheet is given below:

Faults

Back to Main Page | Gridlines

Instructions: Each fault box can be edited by the user to create a new fault scenario. In general, BLUE font values indicate inputs. Excel formulas can be added if needed to calculate costs from input rates and times. The values for **Component**, **Down Time**, and **Total Cost** are the outputs, and are automatically placed into the **Component Faults Table (Table 2)** on the **Main** page. See the comments (red corners) attached to cells in the **Fault 1** table for details.

Fault 1		
Component	Gearbox	
Time Data		Units
Down Time ====>	900	Hours
Labor Time	500	Man-Hours
Crane Rental Time	30	Days
Rates		
Labor Rate	$ 85.00	per Hour
Crane Rental Rate	$ 2,500.00	per Day
Parts & Equipment Costs		
New Gearbox	$ 130,000	
Crane Setup	$ 100,000	
Crane Takedown	$ 100,000	
Crane Rental	$ 75,000	
Supplies	$ 500	
Total Costs		
Parts & Equipment	$ 405,500	
Labor	$ 42,500	
Other Services		
Total Cost ====>	$ 448,000	

Fault 2		
Component	Generator	
Time Data		Units
Down Time ====>	875	Hours
Labor Time	320	Man-Hours
Crane Rental Time	14	Days
Rates		
Labor Rate	$ 85.00	per Hour
Crane Rental Rate	$ 2,500.00	per Day
Parts & Equipment Costs		
New Generator	$ 62,500	
Crane Setup	$ 100,000	
Crane Takedown	$ 100,000	
Crane Rental	$ 35,000	
Supplies	$ 750	
Total Costs		
Parts & Equipment	$ 298,250	
Labor	$ 27,200	
Other Services		
Total Cost ====>	$ 325,450	

Fault 3		
Component	Rotor	
Time Data		Units
Down Time ====>	850	Hours
Labor Time	230	Man-Hours
Crane Rental Time	9	Days
Rates		
Labor Rate	$ 85.00	per Hour
Crane Rental Rate	$ 2,500.00	per Day
Parts & Equipment Costs		
New Blade	$ 45,000	
Crane Setup	$ 100,000	
Crane Takedown	$ 100,000	
Crane Rental	$ 22,500	
Supplies	$ 350	
Total Costs		
Parts & Equipment	$ 267,850	
Labor	$ 19,550	
Other Services		
Total Cost ====>	$ 287,400	

Fault 4		
Component	Hydraulic System	
Time Data		Units
Down Time ====>	72	Hours
Labor Time	32	Man-Hours
Rates		
Labor Rate	$ 85.00	per Hour

Fault 5		
Component	Electrical System	
Time Data		Units
Down Time ====>	280	Hours
Labor Time	50	Man-Hours
Rates		
Labor Rate	$ 85.00	per Hour

Fault 6		
Component	Control Electronics	
Time Data		Units
Down Time ====>	8	Hours
Labor Time	16	Man-Hours
Rates		
Labor Rate	$ 85.00	per Hour

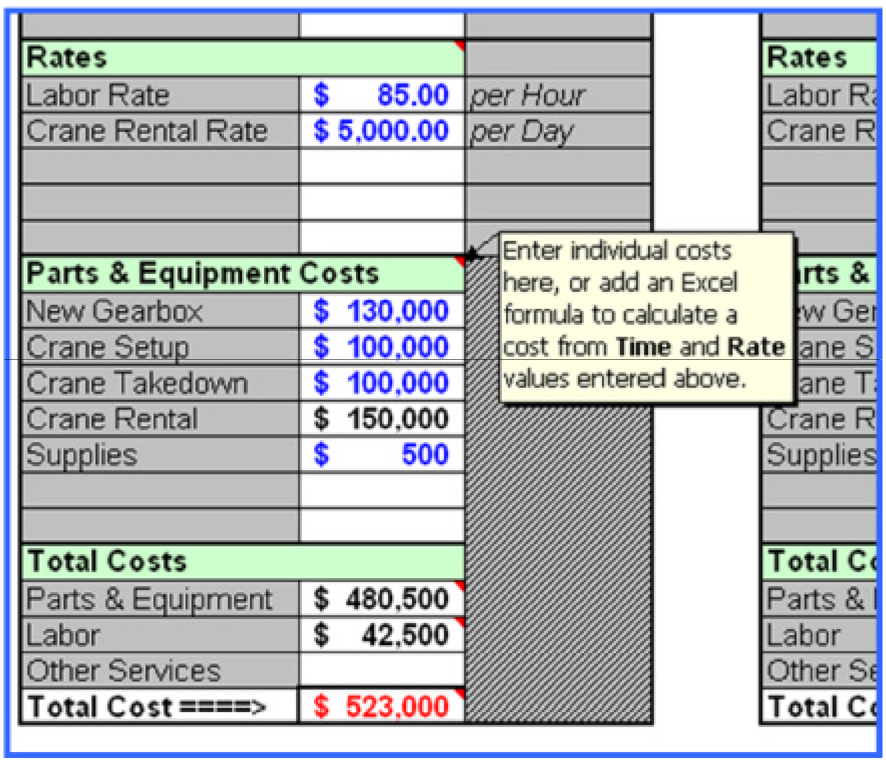
A close-up screenshot of one of the faults from the above spreadsheet is given below, highlighting the user inputs in blue font and output in red font:

Fault 1		
Component	Gearbox	
Time Data		Units
Down Time ====>	900	Hours
Labor Time	500	Man-Hours
Crane Rental Time	30	Days
Rates		
Labor Rate	$ 85.00	per Hour
Crane Rental Rate	$ 2,500.00	per Day
Parts & Equipment Costs		
New Gearbox	$ 130,000	
Crane Setup	$ 100,000	
Crane Takedown	$ 100,000	
Crane Rental	$ 75,000	
Supplies	$ 500	
Total Costs		
Parts & Equipment	$ 405,500	
Labor	$ 42,500	
Other Services		
Total Cost ====>	$ 448,000	

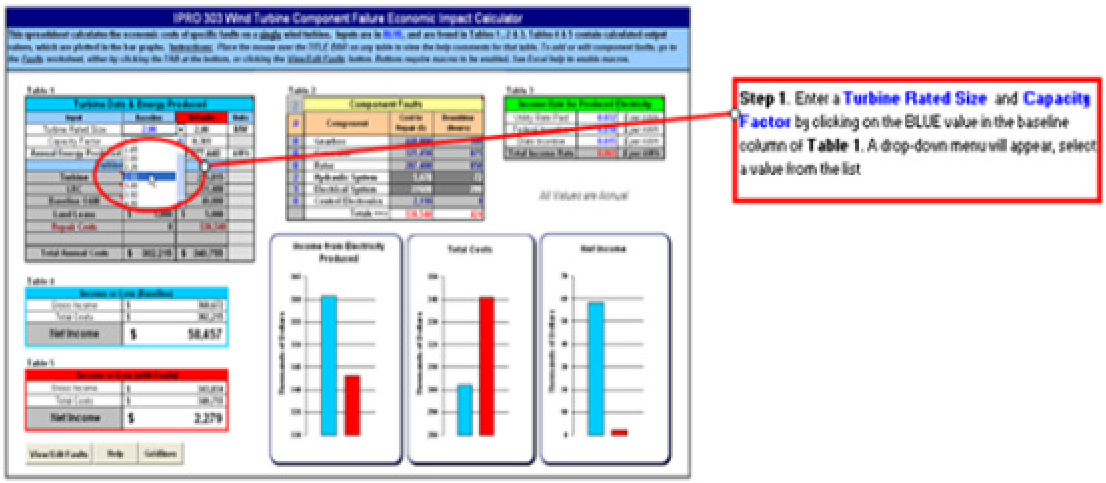
The key figures from each fault table in this sheet are automatically displayed on the main worksheet, such as the component name, total cost to repair and the down-time. The table that is populated in the main worksheet is given below: (Note the totals in this example are 0, since no failures are selected in the # column.)

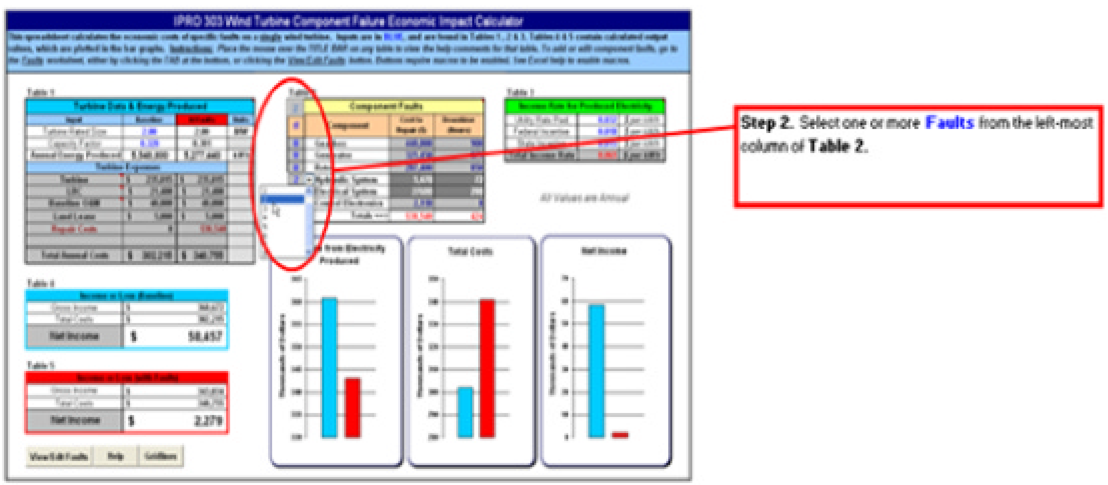
Z	Component Faults		
#	Component	Cost to Repair ($)	Downtime (Hours)
0	Gearbox	448,000	900
0	Generator	325,450	875
0	Rotor	287,400	850
0	Hydraulic System	5,470	72
0	Electrical System	27600	280
0	Control Electronics	2,110	8
	Totals ==>	$0	0

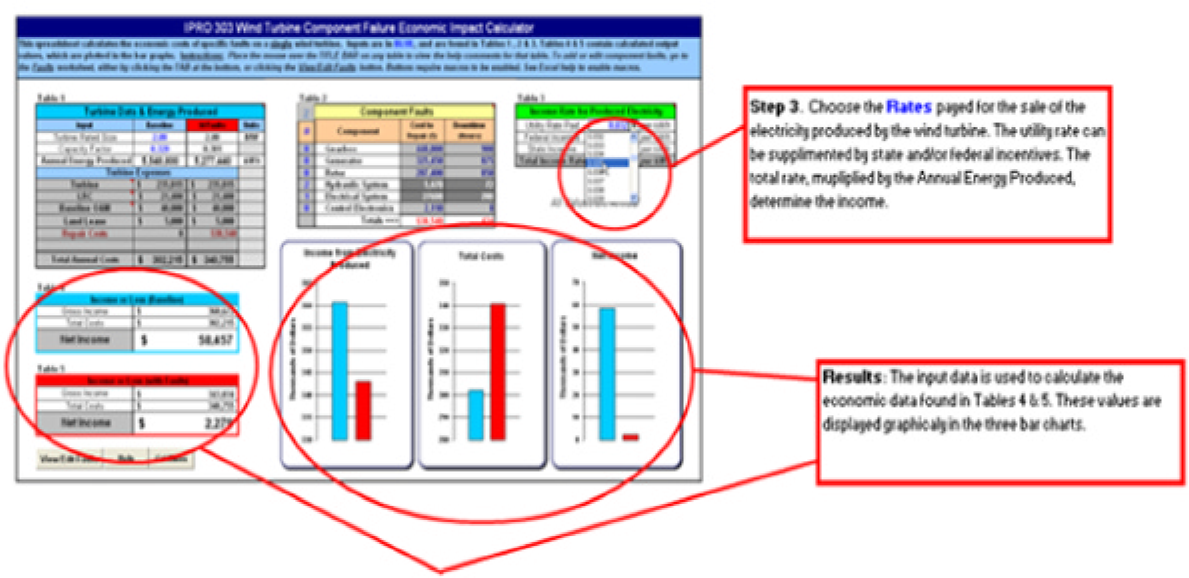
The workbook includes several help features to assist first-time users. These help features include a separate spreadsheet in the workbook with comments on various options in the main worksheet. In addition, extensive pop-up balloon comments were attached to the cells in the tables that explain the required input to the user. The user simply points to the red corner-flag to read the pop-up help message. A screenshot of the first fault table with balloon pop-up messages is given below:



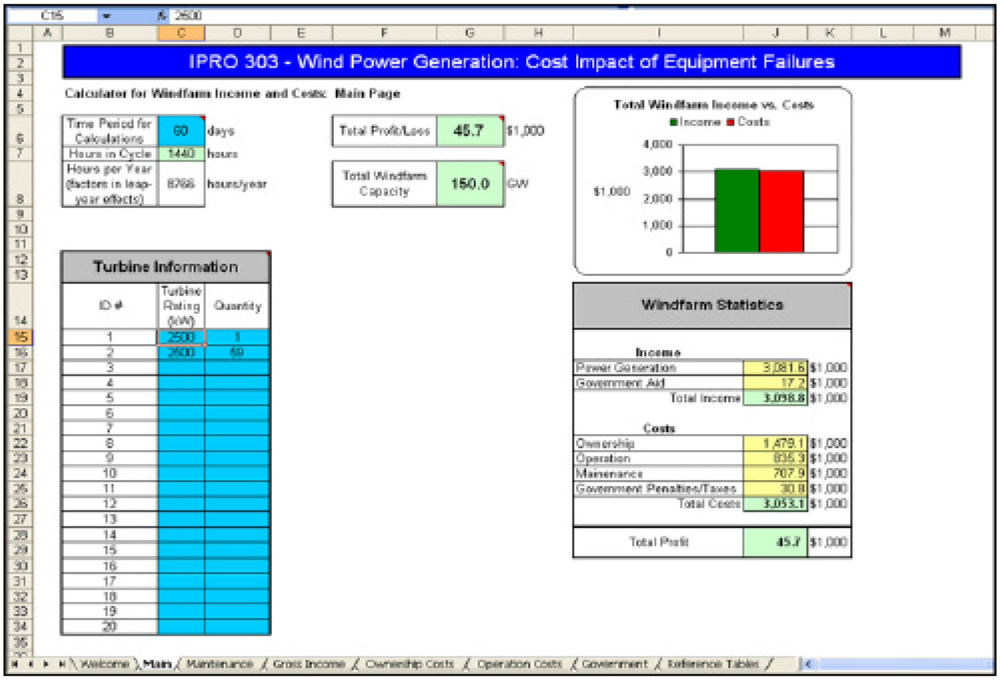
As mentioned above, the second help feature in the workbook is a separate sheet with screenshots of the main worksheet. This screenshots includes comments that instruct the user on what to do on a step by step basis. This is shown on the following page:


IPRO 303 Wind Turbine Component Failure Economic Impact Calculator
Step 1. Enter a Turbine Rated Size and Capacity Factor by clicking on the BLUE value in the baseline column of Table 1. A drop-down menu will appear, select a value from the list

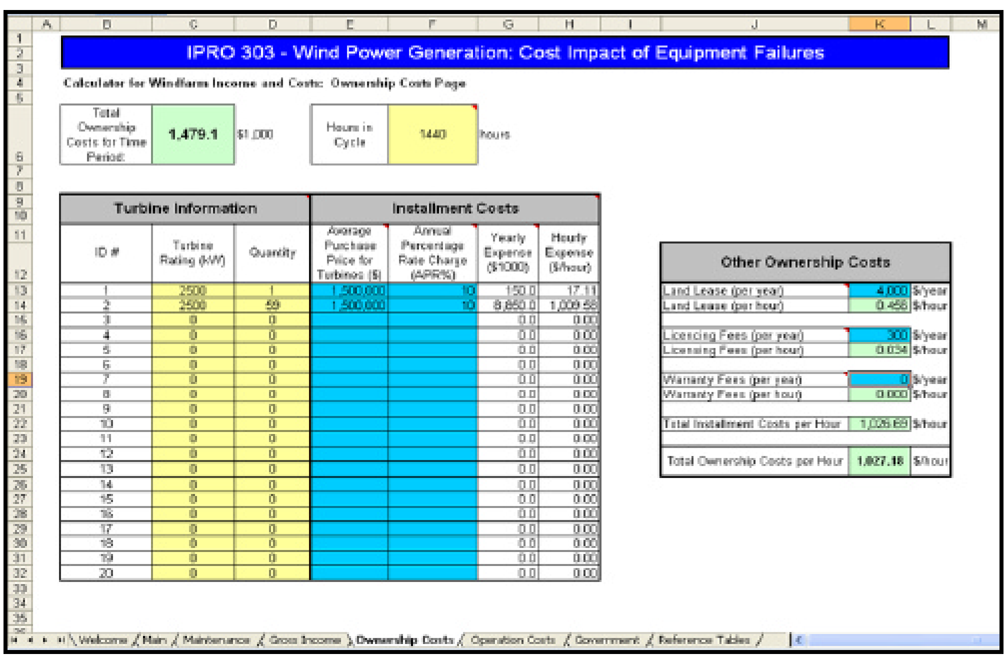

IPRO 303 Wind Turbine Component Failure Economic Impact Calculator
Step 2. Select one or more Faults from the left-most column of Table 2.


IPRO 303 Wind Turbine Component Failure Economic Impact Calculator
Step 3. Choose the Rates payed for the sale of the electricity produced by the wind turbine. The utility rate can be supplimented by state and/or federal incentives. The total rate, muplipied by the Annual Energy Produced, determine the income.
Results: The input data is used to calculate the economic data found in Tables 4 & 5. These values are displayed graphicaly in the three bar charts.

Calculator for Wind Farm Income and Costs: This workbook is intended to give insights into the revenues and costs associated with owning and operating a wind farm that has multiple turbines. The spreadsheet accepts user input in the form of turbine sizes and specifications and calculates output. The workbook takes into account maintenance cost, gross income, ownership costs, operation costs and government incentives. A screenshot of a the main spreadsheet which gives incomes and costs for the entire farm based on all turbines operating at that given time is shown below:



A second screenshot shows the ownership costs associated with owning turbines. This sheet in the workbook gives the user total ownership costs based on inputs of licensing fees, land lease costs, installment costs and actual turbine costs. The screenshot is given below:



D. ETHICAL ISSUES

IPRO 303 discussed the following ethical issues:

1. Ethics and Business Integrity issues regarding SmartSignal's desire that we not disclose that SmartSignal is our sponsor.
2. How we feel about potential unequal contribution or effort among individual IPRO team members.
3. How communication among IPRO team members may be impacted by our cultural diversity.

The class broke into three teams. Each team focused on a specific ethics perspective:

1. The Seven Layers of Integrity by Dr. June Ferrill
2. It's Good Business by Kristine R. Hanson, Robert C. Solomon
3. Professional Engineering Code of Ethics by the American Society of Mechanical Engineers

Each team was to prepare a memo based on their ethics perspective and relate it to each of the three ethical issues. The memos were then presented in class to discuss the issues as a whole. Although we all studied different perspectives, we were able to discuss the issues to come up with common solutions. In regards to not disclosing SmartSignal's name, will not disclose their name to our contacts, and we will also not disclose our contacts' names to SmartSignal. We feel this is a fair solution. When we have a team member who is contributing equally, they should be contacted to improve the situation. Fortunately, we did not encounter this problem over the course of the semester. For the last situation, cultural differences may affect our communication, and we need to be aware of this, as well any other things that could affect our communication so we can work through it. Our team critically examined these issues, and will strive to hold ourselves to the ethical standards expected of us as part of the IPRO program and the Illinois Institute of Technology community.

8. Obstacles

The team faced many obstacles during the semester and dealt with them in a number of ways. Some of the more significant obstacles are given below:

I. Understanding the goals: There were initial problems in trying to specifically decipher the information from the first conference phone call with the sponsor representative. The team ended up working off what it could gather and used a critique of its midterm accomplishments from the sponsor to help clarify objectives.

II. Establishing contacts in industry: It took the team a fairly long time to have solid contacts in the industry. Good contacts with useful information were hard to obtain. A couple of good responsive contacts were eventually generated.

III. Team organization: At the beginning of the project, the team was lacking structure and the flow of communication was not well established. Group leaders were chosen to better organize the team and foster communication among team members.

IV. Technical background of team members: 12 out of the 13 team members are engineering students (mostly mechanical engineering), while the IPRO had a focus on business oriented information. This put most of the team members out of their comfort zones and was definitely a drawback to the progress of the project. The team had to learn to look at the project from a different perspective in order to provide the desired results.

V. Lack of assertive action: A lot of delay was caused during the project due to reluctance by team members to perform necessary tasks without first of all obtaining team approval.

VI. Documents and Formatting: As many of the team members were not experienced in formatting of official documents, much time was spent on explaining and correcting documents. This became less of an issue as the semester progressed since team members became more proficient in creating documents.

VII. Class atmosphere: It took longer than optimal for all the team members to get comfortable with one another. This may have been caused by the lack of clear student leadership. When team leaders were chosen, a lot of this was resolved and more productive results were obtained.

VIII. Ethical issues: There were ethical issues caused by the sponsor's request to remain confidential. This proved to cause a bit of an issue with regards to giving the sponsor information of companies contacted and disclosure to said companies about the team's motives. After discussions with the sponsor, a non disclosure agreement was reached where the sponsor's involvement was not made known to third party companies and particular company information was not made available to the sponsor.

9. Recommendations

As this was the first semester for this IPRO, many things were learned. Although the past IPRO had the same sponsor, the project scope was quite different. The team faced many obstacles and overcame them in a number of ways, as highlighted in section 8 of the report. However, there were additional recommendations that were made for future IPRO projects, given below:

General: The team learned from experience that it may have been better to establish leadership roles early in the semester. This was because although the team functioned well initially and came together to meet deadlines and deliverables, the process became inefficient as the semester progressed. Instead of waiting for a 'crisis' to emerge, leaders were chosen to remind the team of approaching deadlines and to keep all team members on track. The other advantage of choosing team leaders early was that the decision making process was not arbitrary. This proved to be quite effective as team leaders began making meeting agendas and they ensured that all meetings were productive.

Contact Team: 2-3 members are sufficient to carry out the tasks. Also, it is very important that these members are actively involved in other team activities right from the beginning of the project. For this semester, the contact team members expressed the opinion that they found themselves isolated from the rest of the team, and that they were just telephone operators. Moreover, if the questions were technical in nature, they were uncomfortable as they weren't involved in the initial research stage, and they were uncertain as to the team direction and objectives as time progressed. Failure to do so will result in a poor and unproductive IPRO experience for those members, and this will also adversely affect the overall team progress. The team also found that it is best to start off initially by phone as respondents are more at ease when speaking directly with a student. Then, follow up with an email, written statement of intent/confidentiality etc. Also, it is important that the official team statement not appear to be "legalese", since this would cause further concern for a respondent, who would not want to be quoted or held accountable for possibly inaccurate information.

Research Team: The research team recommended that future teams become familiar with the research done this semester and expand on it. A large number of electronic documents were compiled from the research activities and the next step would be to sort through the information. In addition to this, the new research team could find more information on the actual "cost of maintenance". The research team this semester came across problems when trying to get real numbers for maintenance costs and sometimes had to assume costs. In that sense, the new team could work more with the contact team to get information from people rather than through the internet.

Spreadsheet Team: The new spreadsheet team could enhance the previous spreadsheets by adding more realistic cost estimates. This can be done by applying more research data to the inputs such as for the maintenance costs The spreadsheets could also be combined into a single comprehensive workbook so that all the information is output from a single source. The spreadsheets could also be improved technically, by using programming to create user interfaces. This will enhance the aesthetics of the spreadsheet and will also make it more user-friendly. Incorporating more help options will complement this feature.

10. References

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11. Acknowledgements

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