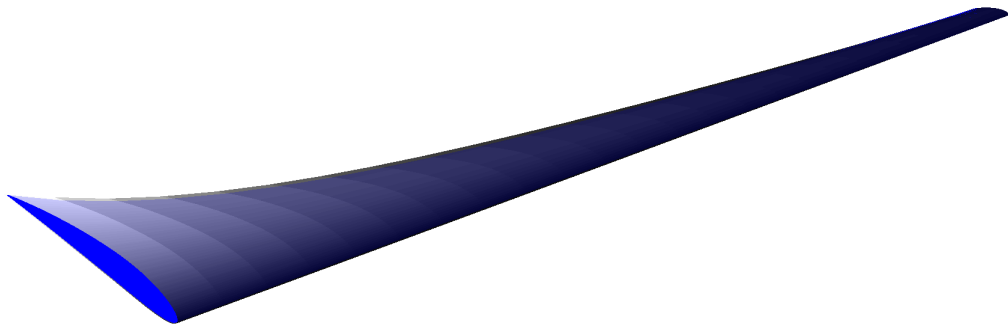


# Small Wind-turbine Rotor Design Code (SWRDC) User's Guide



October 28<sup>th</sup>, 2013

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## Credit

Please cite the following article in all published work involving the use of Small Wind-turbine Rotor Design Code (SWRDC):

Sessarego, M and Wood, D 2015, 'Multi-dimensional optimization of small wind turbine blades' *Renewables: Wind, Water, and Solar*, vol 2, no. 1, pp. 1-11. DOI: 10.1186/s40807-015-0009-x <https://doi.org/10.1186/s40807-015-0009-x>

Credit for the source code development also goes to:

NGPM – A NSGA-II Program in Matlab v1.4

by Song Lin

23 Apr 2011 (Updated 26 Jul 2011)

<http://www.mathworks.com/matlabcentral/fileexchange/31166-ngpm-a-nsga-ii-program-in-matlab-v1-4>

NSGA - II: A multi-objective optimization algorithm

by Aravind Seshadri

19 Mar 2006 (Updated 19 Jul 2009)

<http://www.mathworks.com/matlabcentral/fileexchange/10429-nsga-ii-a-multi-objective-optimization-algorithm>

polygeom.m

by H.J. Sommer

09 Oct 1998 (Updated 30 Nov 2008)

<http://www.mathworks.com/matlabcentral/fileexchange/319-polygeom-m>

NWTC Design Codes (HARP\_Opt by Danny C. Sale)

[http://wind.nrel.gov/designcodes/simulators/HARP\\_Opt/](http://wind.nrel.gov/designcodes/simulators/HARP_Opt/). Last modified Thursday, 28-Feb-2013 17:18:24 MST; accessed Saturday, 23-Mar-2013 12:29:38 MDT.

Multi-objective NSGA-II code in C

by Kanpur Genetic Algorithms Laboratory

Revision 1.1.6 (08 July 2011) (for Linux only- 64-bit bug for binary coding fixed): NSGA-II in C with gnuplot (Real + Binary + Constraint Handling)

<http://www.iitk.ac.in/kangal/codes.shtml>

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<https://web.mit.edu/drela/Public/web/gpl.txt>

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# 1 Introduction

The Small Wind-turbine Rotor Design Code (SWRDC) uses a genetic algorithm, blade element momentum (BEM) theory, simple Euler-Bernoulli beam theory, a model for starting from Wood [1], and a noise model of Zhu [2] to design small-scale, variable-speed and fixed-pitch horizontal-axis wind-turbine rotors. The code is based on the work of a M.Sc. project done at the University of Calgary designed for large-scale wind-turbines, which has been recoded for the purpose of designing small-scale wind-turbine rotors.

The genetic algorithm used in SWRDC is a search heuristic that mimics the process of natural selection. This heuristic (also called metaheuristic) can be used to solve optimization problems such as the design of wind-turbine rotors. Genetic algorithms belong to a larger family called evolutionary algorithms (EA), which generate solutions to optimization problems using techniques inspired by natural evolution, such as selection, crossover and mutation. A set of solutions is called a population and undergoes selection, crossover and mutation to create subsequent generations of superior solutions (or individuals). SWRDC uses a genetic algorithm as described in Deb’s book [3] and BEM and beam theory models described in Hansen [4].

SWRDC can optimize rotors based on a single or multiple criteria. Each criteria is called an objective and is optimized by either minimizing or maximizing its objective function. The rotor design optimization is formulated as a weighted min-max problem:

$$\begin{aligned} \text{minimize} \quad & \max_{i=1}^q w_i \left| \frac{f_i(\mathbf{x}) - z_i^{\min}}{z_i^{\max} - z_i^{\min}} \right| \\ \text{subject to} \quad & \mathbf{x} \in S \end{aligned} \tag{1}$$

where  $q$  is the number of objectives,  $w_i$  are weights that satisfy  $w_i \geq 0$  and  $\sum_{i=1}^q w_i = 1$ ,  $f_i(\mathbf{x})$  are the objective functions,  $z_i^{\max}$  and  $z_i^{\min}$  are the maximum and minimum objective values of the population in the current iteration (or generation), and  $S$  is the feasible region (i.e. region where constraints are satisfied). The objective functions for the small-scale rotor optimization are the power coefficient  $C_P$  or annual energy production  $AEP$ , starting time  $t_s$ , blade mass  $m_{blade}$ , and noise  $SPL_{total}$ . Note  $C_P$  and  $AEP$  are maximized by minimizing the inverse of their objective functions.

## 2 Installing and Uninstalling SWRDC

SWRDC is only supported for Windows operating systems and Microsoft Excel must be installed for outputting the SWRDC optimization results. Furthermore, the GUI of SWRDC requires a minimum screen resolution of 1280 x 768, but a much higher resolution is recommended.

### 2.1 Source Code

If you have the original source code and not the compiled version, you will need an installed version of MATLAB with associated licensing. Toolboxes that do not accompany the standard MATLAB license are not required, with the exception being the “MATLAB Parallel Computing Toolbox” if executing the code in parallel is desired.

### 2.2 Compiled Code

If you have the compiled version of the code, you must have MATLAB Component Runtime (MCR) installed on your computer. The MCR is a standalone set of shared libraries that

will allow you to execute MATLAB code on computers without MATLAB installed and associated licensing. The compiled code must be executed using MCR v7.17, which should accompany the compiled code in a package named SWRDC\_pkg.exe.

Locate SWRDC\_pkg.exe and open it to extract the contents of the package.

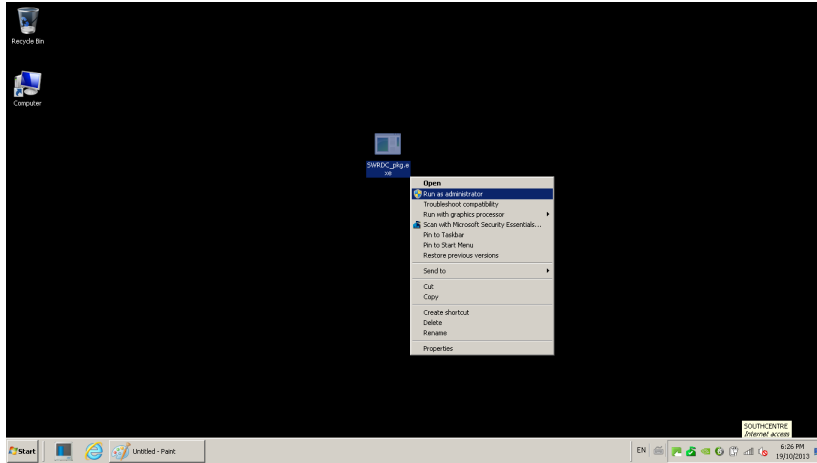


Figure 1: Open the SWRDC package.

The package will automatically extract all of its contents into the directory where the SWRDC\_pkg.exe is held.

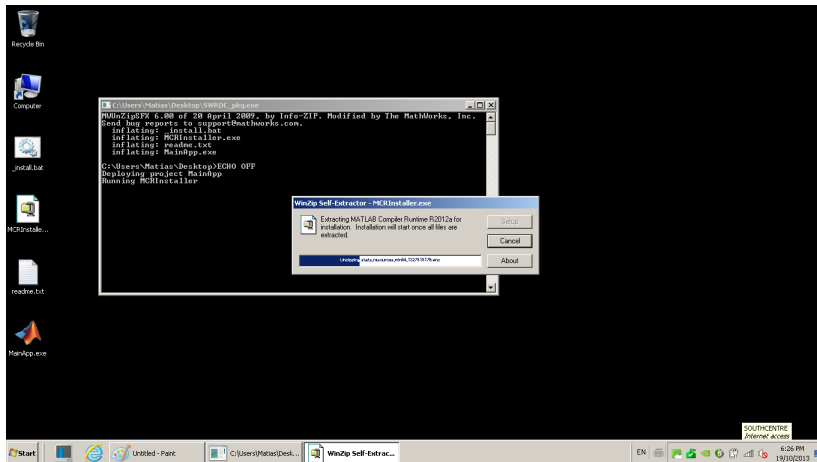


Figure 2: Extracting SWRDC package contents.

The MATLAB MCR installation window should appear automatically. Please follow the instructions to complete the MCR installation.

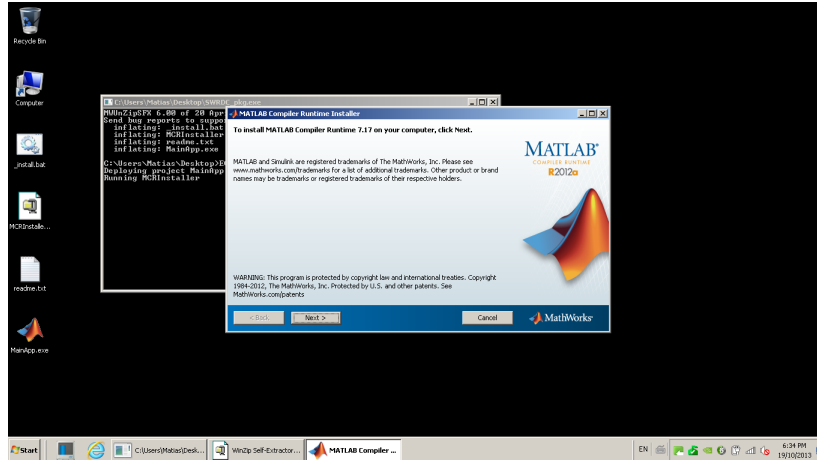


Figure 3: MATLAB MCR installation window.

## 2.3 Uninstalling SWRDC

If you have the original source code, simply delete all files and folders pertaining to the SWRDC program.

If you have the compiled version of the code, delete all contents that came with the SWRDC\_pkg.exe package. If you want to uninstall the MCR, you must locate `uninstall.exe` within the directory where you installed the MCR. For example, if you selected `C:\Program Files\MATLAB\MATLAB Compiler Runtime\v717` as your installation directory, go to `\v717\uninstall\bin\win64\uninstall.exe`

You can also uninstall the MCR by selecting **Uninstall a program** in the control panel of your Windows operating system.

## 3 Folder Structure and Distributed Files

The folder structure and distributed files are described in this section.

### `airfoildatabase\`

In this folder are text files (\*.txt) that contain the aerodynamic data as well as the x-y coordinates for a set of airfoil profiles. The aerodynamic data consists of lift and drag coefficients and the range of Reynolds numbers the coefficients pertain. This folder also holds AirfoilPrep developed by the NWTC, which will allow you to extend the lift and drag coefficients to the  $-180^\circ$  and  $180^\circ$  range of angle of attack.

### `bl_dstar\`

This folder is used to store the boundary layer displacement thickness data (\*.txt) for different angles of attack and Reynolds numbers for the airfoil under consideration. It is used for noise calculation purposes in SWRDC. To analyse in detail the data produced by XFOIL, you may refer to the files stored in this folder.

### `code\`

This folder contains the MATLAB source code files (\*.m) for SWRDC. You may open these files and make adjustments or changes by using the MATLAB editor, but is not recommended. If you have the compiled version of the code, you will not have access to this folder.

### `commandwindow\`



The text displayed in the command window for each optimization run is stored as a text file in this folder.

**documentation\**

This folder contains this user guide and the files used to generate it.

**exportedcoords\**

The X-Y-Z coordinates (\*.txt) for the blade design produced by the optimization is stored in this folder. In addition, this folder holds the `final_blade_shape.txt` file that contains the radius (m), chord (m) and twist (degrees) of the blade. This information can be imported into a CAD program such as SolidWorks, which can then be used for fabrication purposes.

**GUI.settings\**

This folder holds MATLAB figure files (\*.fig) that allow the saving and loading of presets for the SWRDC graphical user interface (GUI). In addition a screenshot of the GUI is stored in this folder as `GUI_Input.bmp` for each optimization run.

**imagesGUI\**

This folder holds JPG (\*.jpg) images incorporated in the GUI. Do not delete or modify any of these files. If you have the compiled version of the code, you will not have access to this folder.

**noisedatabase\**

This folder holds the boundary layer displacement thickness data (\*.dat) for a set of airfoils required for noise analysis.

**output\**

This folder contains the Excel (\*.xls) files summarizing the optimization results. Do not delete the `TEMPLATE_Do_Not_Delete.xls` file. This is a template used for outputting the results. You can edit the formatting such as font size, graph colour, etc. of the output Excel file by modifying this template.

**turbinedatabase\**

This folder holds blade data (\*.txt) containing the radius (m), chord (m) and twist (degrees) distributions for existing turbines. The blade design and performance determined from SWRDC can be compared with this data.

**wind\_data\**

This folder holds windspeed probability distribution data (\*.dat) for specific sites. You may store and load windspeed probability data by using this folder.

**xfoil.exe**

This is the standalone executable for XFOIL developed by Mark Drela and is used for noise analyses. Do not delete or modify this file.

**SWRDC.m**

The MATLAB script (\*.m) used to start the SWRDC program. If you have the compiled version of the code, you will have a file named `SWRDC.exe` instead.

**README\_FIRST\_LICENSE.txt**

The read me and license text file that must be read and fully understood prior to installing and using the SWRDC software.

## 4 Starting SWRDC

### 4.1 Source Code

After opening MATLAB and selecting the SWRDC directory, right click on the `SWRDC.m` file and click `Run`. Alternatively, type `SWRDC` in the command window. A GUI should appear as shown in Figure 4. Do not click `Run Optimization` on the GUI while in a directory other than the one that holds the `SWRDC.m` file.

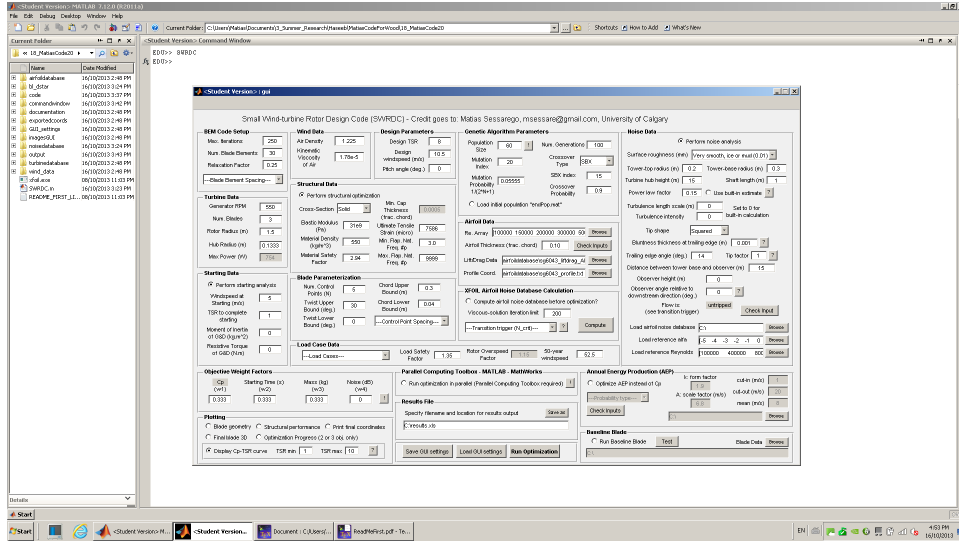


Figure 4: SWRDC graphical user interface (GUI).

## 4.2 Compiled Code

Locate the SWRDC directory and open `SWRDC.exe`. The program may take 5 minutes or longer to initialize. Please be patient and wait for the GUI to appear.

## 5 Using the GUI

This section will explain all components of the SWRDC GUI and how to apply the appropriate settings. If you are searching for information of a particular component, you may refer to the relevant subsection.

### 5.1 BEM Code Setup

The **BEM Code Setup** panel is used to adjust the BEM algorithm parameters in SWRDC. The panel consists of three text boxes for the `Max.Iterations`, `Num.Blade Elements`, and `Relaxation Factor` parameters as well as a drop-down menu for the `---Blade Element Spacing---`. The BEM analysis in SWRDC involves an iterative technique, which requires a small (1-20) or large (200+) number of iterations to estimate the aerodynamic performance of a rotor design. The appropriate number of iterations required depends on the wind turbine under consideration and the value chosen for the relaxation factor.

A small number for the relaxation factor will ensure that the BEM algorithm will converge to the final solution. However, reducing this factor will at the expense require a greater number of iterations. To guarantee accurate aerodynamic calculations, set the maximum number of iterations to a large value (200+) and the relaxation factor to a small number (<0.2). For quick and rough calculations, apply the opposite settings.

The number of blade elements parameter controls the resolution of the aerodynamic results. Set this value to a large number for a slow and accurate calculation. For quick and rough calculations, set this value to a small number.

The blade element spacing allows the resolution of the aerodynamic computations to be concentrated on specific regions of the blade. For example, if `half-cosine` (`finer`

towards tip) is selected, the resolution at the blade tip will be high but the resolution at the root will be low. The `full-cosine` option produces equal resolution at the tip and hub, but a low resolution in the middle.

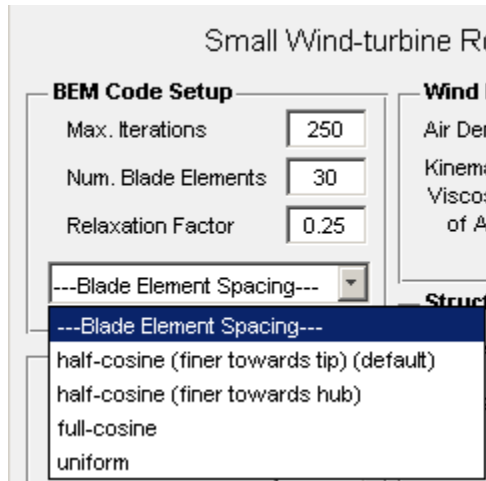


Figure 5: BEM code setup panel.

## 5.2 Turbine Data

Basic turbine data is entered into the `Turbine Data` panel. This data includes the maximum allowable generator RPM (revolutions per minute), number of blades, rotor and hub radii, and maximum allowable generator or rotor power.

The radius is measured from the centre of rotation (i.e.  $\text{radius} = 0$  at centre of rotation). Therefore, the hub radius is the distance measured from the centre of rotation and the outer radius of the hub. The rotor radius is the distance measured from the centre of rotation and the tip of the blade. Note the blade precone is always set to zero, and thus the swept radius is equal to the rotor radius.

The maximum power is enabled only if the `Optimize AEP instead of Cp` option is selected in the `Annual Energy Production (AEP)` panel. Otherwise, it is not necessary to input this value. The efficiency of conversion from mechanical to electrical power is assumed to be 100% always.

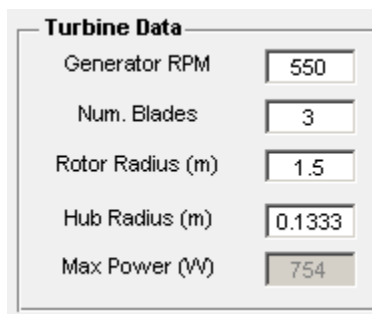
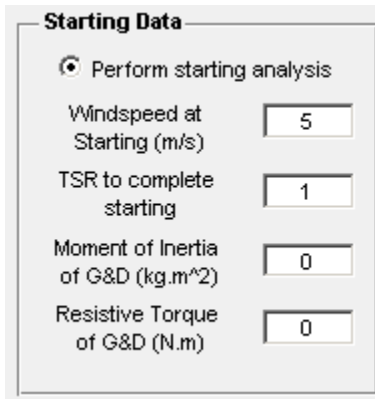


Figure 6: Turbine data panel.

### 5.3 Starting Data

This panel contains the data required for the starting model described in Wood [1]. If **Perform starting analysis** is selected, the optimization will minimize the time required for the turbine to start. The input **Windspeed at Starting** is the windspeed the turbine should start. Increasing the starting windspeed will allow the turbine to start more easily, since a higher windspeed will increase the starting torque. A turbine with good starting performance will be able to start at a low windspeed for this input field. The moment of inertia and the resistive torque of the generator and drivetrain (G&D) will increase the wind-turbine starting time. Unless this information is available for the generator and drivetrain you have selected for the wind turbine design, input zero for these fields.

Note that blades may produce a starting time of 701, 901, or 1101. These numbers are not the result of starting calculations, but a penalty placed for blades that are unable to start. If the blade optimization produces any of these three numbers several times, the inputs in the starting data panel should be changed in a way to promote starting. This can be achieved by increasing the starting windspeed or decreasing the G&D inputs. It is also important to be aware that the starting time should be interpreted as a relative quantity. As explained in Wood [1], the model cannot be used to calculate the actual “time” for starting. In order to compute starting time realistically, the model requires the issues discussed in [1] to be addressed.



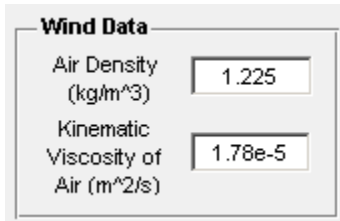
The image shows a software panel titled "Starting Data". It contains a radio button labeled "Perform starting analysis" which is selected. Below this are four input fields: "Windspeed at Starting (m/s)" with the value 5, "TSR to complete starting" with the value 1, "Moment of Inertia of G&D (kg.m^2)" with the value 0, and "Resistive Torque of G&D (N.m)" with the value 0.

Parameter	Value
Windspeed at Starting (m/s)	5
TSR to complete starting	1
Moment of Inertia of G&D (kg.m <sup>2</sup> )	0
Resistive Torque of G&D (N.m)	0

Figure 7: Starting data panel.

### 5.4 Wind Data

The wind data panel allows the density and kinematic viscosity of air in the wind to be specified.



The image shows a software panel titled "Wind Data". It contains two input fields: "Air Density (kg/m^3)" with the value 1.225 and "Kinematic Viscosity of Air (m^2/s)" with the value 1.78e-5.

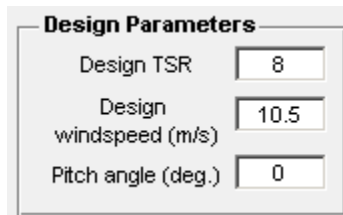
Parameter	Value
Air Density (kg/m <sup>3</sup> )	1.225
Kinematic Viscosity of Air (m <sup>2</sup> /s)	1.78e-5

Figure 8: Wind data panel.

## 5.5 Design Parameters

SWRDC is designed for variable-speed turbines that can operate at a single tip-speed ratio (TSR) between the windspeed at starting and the windspeed at which the maximum generator RPM is reached. This TSR is called the design TSR, and must be specified by the user. If the turbine is to be modelled as a fixed-speed, the design TSR is equal to  $\frac{\omega R}{V_o}$  where  $\omega$  is the generator's RPM converted to rad/s,  $R$  is the rotor radius, and  $V_o$  is the design windspeed. Note that for the fixed-speed case, the **Display Cp-TSR curve** in the **Plotting** panel and the **Optimize AEP instead of Cp** in the **Annual Energy Production (AEP)** panel should be disabled, since these have been programmed for variable-speed operation only. Careful consideration should be given for the design TSR and windspeed, since the rotor design will be significantly influenced by these two inputs.

The pitch angle is the angle between the tip chord and the rotorplane. SWRDC allows for fixed-pitch turbines only. If a baseline blade is provided in the **Baseline Blade** panel that has a pitch angle of  $0^\circ$  and a negative or positive value of twist for the blade tip, SWRDC will automatically recalculate the twist distribution such that the twist at the tip becomes zero. The pitch angle will then be set to the previous value of twist at the blade tip. The recalculated twist distribution and pitch produces an identical local pitch (local pitch = twist + pitch) as the original configuration. During the optimization, the tip twist is assumed to be zero always. If the user desires a negative or positive value for twist towards the blade tip, he or she must specify the appropriate pitch angle to take this into account.



Design Parameters	
Design TSR	8
Design windspeed (m/s)	10.5
Pitch angle (deg.)	0

Figure 9: Design parameters panel.

## 5.6 Structural Data

If the **Perform structural optimization** option is enabled, SWRDC will minimize the blade mass while satisfying a maximum allowable strain. During the structural analysis, the blade is modeled as a simple beam with isotropic material properties. The blade cross-section can be modelled as solid or as a thin shell. The strain is calculated at points on the cross-section where its magnitude is the largest. Maximum strain typically occurs on the highest and lowest points of the upper and lower surfaces of the cross-section respectively.

To select whether the blade should be modelled as solid or hollow, use the **Cross-Section** drop-down menu. If solid is selected, SWRDC will use the structural analysis to determine whether a candidate blade is structurally feasible or infeasible. If hollow is selected, the shell thickness along the length of the blade will be calculated such that each blade element does not exceed the maximum allowable strain. You must also specify the minimum shell thickness as a fraction of the chord length using the **Min.Cap Thickness** field to avoid the possibility of an infinitely thin blade element.

When modelling the blade using isotropic material properties, the **Elastic Modulus**, **Ultimate Tensile Strain** and **Material Density** of the material used for the blade fabrication is required. The ultimate tensile strain is the strain at the point on the stress-strain curve where stress is a maximum. The stress-strain curve is obtained from a tensile test.

If desired, a **Material Safety Factor** can be applied on the ultimate tensile strain. The structural analysis in SWRDC does not take fatigue effects into account.)

The minimum and maximum flapwise natural frequency fields (i.e. **Min.Flap.Nat.Freq.** and **Max.Flap.Nat.Freq.**) are used for the analysis of blade natural frequencies. As a general rule of thumb, the first flapwise natural frequency of the blade should be between  $4p$  and  $5p$ , with  $p$  being the rotational frequency of the rotor, while the first edgewise natural frequency of the blade should be close to  $6.5-7p$ , to comply with good first-frequency separation requirements. Separating the blade natural frequencies from the harmonic vibration associated with rotor rotation will prevent the occurrence of resonance. To exclude frequency analysis in the optimization, enter 0 and 9999 for the **Min.Flap.Nat.Freq.** and **Max.Flap.Nat.Freq.** fields respectively.

If the **Perform structural optimization** option is disabled, the optimization will not attempt to minimize the mass but will still perform structural computations. The optimization will determine if a candidate blade is structurally feasible or infeasible unless an infinite maximum strain is specified in the **Ultimate Tensile Strain** field. The structural computations are required for the estimation of starting time, since starting depends on the inertia of the blade. To compute the inertia, the blade will be assumed solid and will use the elastic modulus and material density specified in the **Structural Data** panel.

Structural Data	
<input checked="" type="radio"/> Perform structural optimization	
Cross-Section	Solid
Elastic Modulus (Pa)	31e9
Material Density (kg/m <sup>3</sup> )	550
Material Safety Factor	2.94
Min. Cap Thickness (frac. chord)	0.0005
Ultimate Tensile Strain (micro)	7586
Min. Flap. Nat. Freq. #p	3.0
Max. Flap. Nat. Freq. #p	9999

Figure 10: Structural data panel.

## 5.7 Load Case Data

The load case data is solely used for the structural component of SWRDC. Only two load cases are available: **Parked Condition (default)** and **Rotor Overspeed**. The parked condition simulates a hurricane whereby the rotor is stationary and is subjected to an extreme windspeed in all directions (i.e.  $0^{\circ}$ - $360^{\circ}$  around the blade axis). The **Rotor Overspeed** case simulates an incoming wind normal to the rotor plane that will cause the rotor to rotate beyond the maximum allowable RPM of the generator.

The **50-year windspeed** field is used to specify the extreme windspeed for both the parked and rotor overspeed cases. The loads associated with the extreme windspeed will be multiplied by the **Load Safety Factor** value. The **Rotor Overspeed Factor** is enabled for the rotor overspeed load case only. If a load case associated with normal operation is desired, select the **Rotor Overspeed** load case, a **Rotor Overspeed Factor** of 1, and a windspeed considered as normal in the **50-year windspeed** field.



Figure 11: Load case data panel.

## 5.8 Blade Parameterization

Bézier curves that are manipulated by control points (CPs) define the blade twist and chord distributions. The twist and chord are both required to be monotonically decreasing. The dimensional thickness is the product of the relative thickness and the chord. The relative thickness is defined in the `Airfoil Thickness (frac.chord)` field in the `Airfoil Data` panel (see section 5.10). Figure 12 illustrates the blade parameterization.

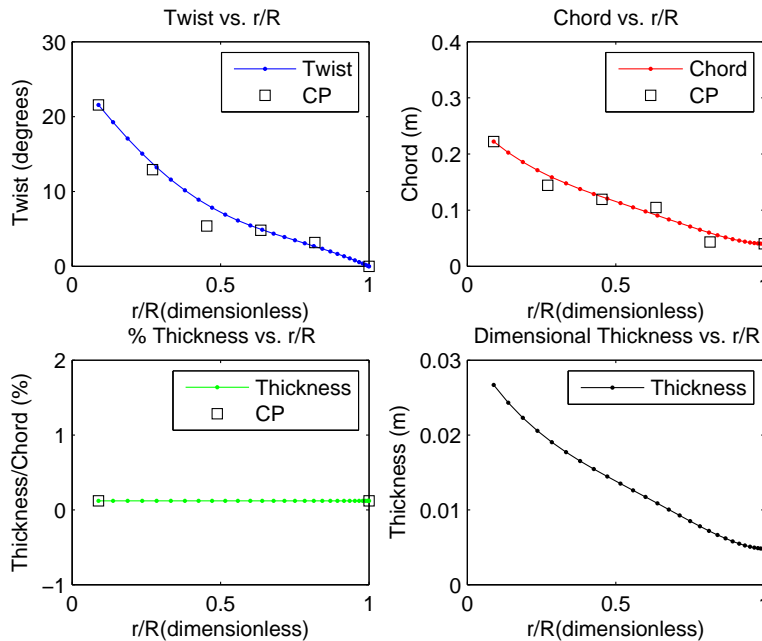


Figure 12: Control points (CPs) determine the blade element (BE) values for twist and chord. The dimensional thickness is the product of the relative thickness and the chord.

The number of CPs that determine the twist and chord can be adjusted using the `Num.Control Points (N)` field. Increasing the number of CPs increases the complexity of the Bézier curve making it bend more.

The radial location of the CPs are fixed and distributed according to the spacing chosen in the `---Control Point Spacing---` drop-down menu. There are four options available: `uniform (default)`, `half-cosine (finer towards hub)`, `half-cosine (finer towards tip)` and `full-cosine`. In the `half-cosine (finer towards hub)` option, CPs are spaced with higher density towards the hub and lower density towards the tip. The `half-cosine (finer towards tip)` is the opposite of `half-cosine (finer towards hub)`. In the `full-cosine` option, CPs are spaced with higher density near the hub and tip, but lower density in the middle. The `---Control Point Spacing---` option allows the blade to be designed with greater maneuverability in specific regions.

The **Twist Upper Bound**, **Twist Lower Bound**, **Chord Upper Bound**, and **Chord Lower Bound** fields determine the upper and lower bounds for the CPs controlling the twist and chord. Note when entering the **Twist Lower Bound** that there is an additional CP for twist at the blade tip which is set to zero (hard-coded in). To apply a twist other than zero at the blade tip, you must make the appropriate adjustment using the **Pitch angle (deg.)** field in the **Design Parameters** panel (see section 5.5).

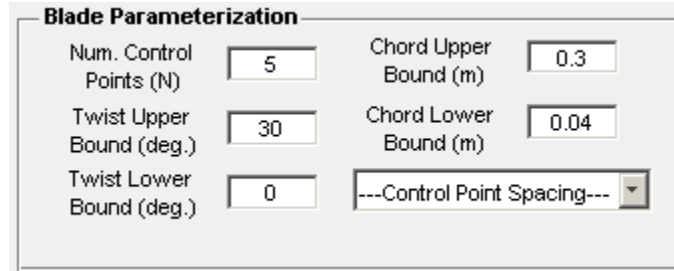


Figure 13: Blade parameterization panel.

## 5.9 Genetic Algorithm Parameters

SWRDC uses a genetic algorithm (GA) as the optimization algorithm, which can be controlled using the **Genetic Algorithm Parameters** panel. The first parameter is **Population Size**, which determines the number of individuals for each generation. Increasing the population size allows the GA to search more thoroughly the design space and hence obtain a better result. However, increasing the population size will also increase the time to compute each generation. The overall computing time scales linearly with **Population Size**. The size of the population must also be a number that will produce an integer when divided by four. The GA within SWRDC will not function otherwise. A population size larger than 100 is recommended.

The **Num. Generations** parameter is the maximum number of generations that the GA will run before it terminates. The GA may, however, terminate sooner if the population converges to a single optimum solution. Increasing **Num. Generations** will ensure the GA converges to the optimal blade design. A number larger than 50 for **Num. Generations** is recommended.

To create children and potentially superior individuals, the GA utilizes the crossover and mutation operators. Each operator contains settings which can be controlled by the user. These settings can significantly influence the performance of the GA. For **Crossover Type**, either **SBX** or **Uniform** can be selected. For the **SBX**, the crossover is performed between two parents according to a scheme described in Deb [3] and requires a **SBX index**. The **SBX index** controls the probability of creating near parent solutions or distant solutions as children. When **Uniform** is selected, a random binary vector is created and selects the genes where the vector is 1 from the first parent and the genes where the vector is a 0 from the second parent, and combines the genes to form the child. The **Crossover Probability** controls whether two parents will be subjected to crossover or not, and is a parameter for both the **SBX** and **Uniform** crossover types.

Mutation specifies how the GA makes small random changes to create mutated children, promoting the diversity of the population. Only polynomial mutation as described in Deb [3] is available, which depends on the **Mutation Index** and **Mutation Probability** parameters. The **Mutation Index** controls the intensity of the mutation (or the randomness) when altering the genes of a child. The **Mutation Probability** is the probability that each



gene from a child will be mutated. A commonly used heuristic for **Mutation Probability** is  $1/\text{number of variables}$ , where the number of variables in SWRDC is  $2N + 1$ .  $N$  is the number of control points as specified in the **Num.Control Points (N)** field on the **Blade Parameterization** panel.

The last option, **Load initial population "endPop.mat"**, allows the user to input a population from a previous optimization as the initial population. For each optimization run and for each generation, a file named **endPop.mat** will be stored in the SWRDC directory. By loading **endPop.mat** from a previous optimization, the GA begins the blade design process using an already improved population instead of one generated at random.

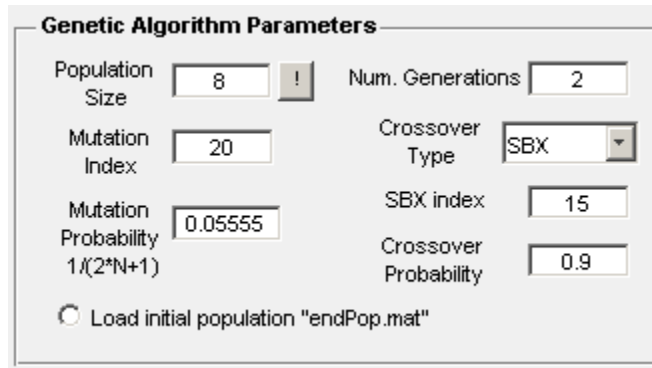


Figure 14: Genetic algorithm parameters panel.

## 5.10 Airfoil Data

The **Airfoil Data** panel is where all the airfoil data for the aerodynamic and structural analyses is entered. The **Re.Array** field is where the range of Reynolds numbers for the airfoil lift and drag data is loaded. The length of **Re.Array** must match the number of lift and drag data entered in the **Lift/Drag Data** field. To enter **Re.Array**, you can either type the Reynolds numbers in the text box or load it from a file using the **Browse** button. If typing Reynolds numbers in the text box, remember to enclose them with square brackets (i.e. []).

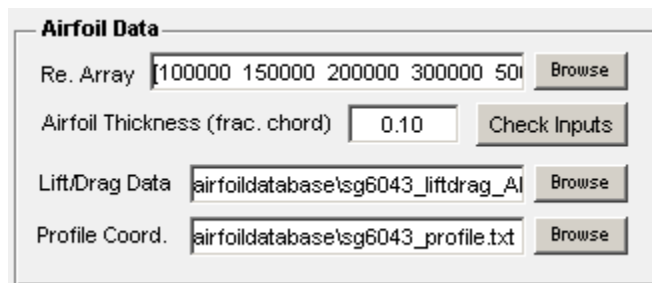


Figure 15: Airfoil data panel.

**Airfoil Thickness (frac.chord)** is the relative thickness (dimensional thickness/chord) of the airfoil being used in the blade design. This value is for plotting purposes only and does not need to be exact. In the structural analysis, the relative thickness is calculated using the profile coordinates entered in the **Profile Coord.** field. To load the lift and drag data,

and the profile coordinates, use the **Browse** button. Note the lift and drag data, and profile coordinates must be located in the `\airfoildatabase` folder in the SWRDC directory.

You can check if all your data has been entered correctly by clicking on the **Check Inputs** button. A figure displaying all of your data should appear as shown in Figure 16. If the data was not properly entered, the message “—!!!!PLEASE CHECK YOUR AIRFOIL DATA!!!!—” will appear on the MS-DOS window if you are using the compiled version, or the MATLAB command window if you are using the source code.

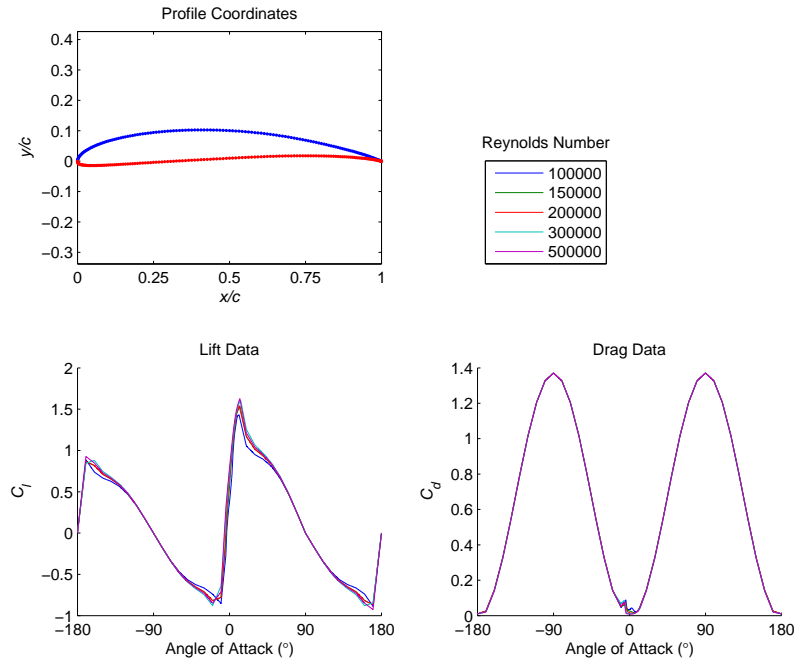


Figure 16: Airfoil data checking.

## 5.11 XFOIL Airfoil Noise Database Calculation

SWRDC includes an automated noise database calculation algorithm using the XFOIL code developed by Mark Drela [5]. The noise database pertaining to the airfoil used in the blade design is necessary to perform noise analyses. The database consists of boundary layer displacement thickness values for different Reynolds numbers and angles of attack.

The database can be computed before an optimization begins by selecting the **Compute airfoil noise database before optimization?** option. If selected, you do not need to load a file for the **Load airfoil noise database** field in the **Noise Data** panel, but do need to specify the range of Reynolds numbers and angles of attack in the **Load reference alfa** and **Load reference Reynolds** fields. Default values are included in the GUI for your convenience. The noise database calculation is performed soon after the **Run Optimization** button is pressed and before the optimization begins. The alternative is to compute the database and store it as a file by clicking on the **Compute** button. You must then load this file on the **Load airfoil noise database** field.

The **Viscous-solution iteration limit** controls the maximum number of iterations for XFOIL to converge to a solution. Increasing the number of iterations will increase the

chances of obtaining an accurate noise database, but will also increase the computing time for the database calculation. XFOIL will often not converge to a solution and the accuracy of the database will be adversely affected. A default value of 200 is included in the GUI as reference.

The drop-down menu labelled `---Transition trigger (N_crit)---` provides two options: `untriggered:N_crit=9` (default) and `triggered:N_crit=4`. For details concerning this option, refer to section 7.4, the thesis of Zhu [2], or the XFOIL user guide on the XFOIL website: <http://web.mit.edu/drela/Public/web/xfoil/>. Whether the untriggered or triggered option is selected will be reflected in the Noise Data panel on the right of the “Flow is:” text as shown in Figure 18.

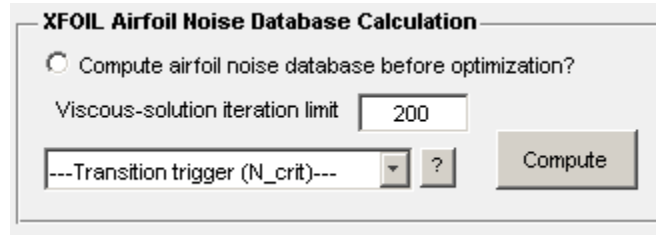


Figure 17: XFOIL airfoil noise database calculation panel.

## 5.12 Noise Data

If the `Perform noise analysis` option is enabled, SWRDC will minimize the noise emission by altering the blade’s shape. Several parameters are necessary in order to estimate noise involving the location of the rotor relative to the observer’s position, wind characteristics, and parameters that influence the aero-acoustics near the blade sections and tip. Fields are accompanied with a short text and a few have help buttons to assist the user in selecting the appropriate settings. Here are a few additional notes:

- For `Power law factor`, you may refer to the notes in section 7.3.1.
- The `Turbulence length scale` and `Turbulence intensity` fields should be set to zero unless for specific research purposes.
- The `Tip shape` can either be `Squared` or `Rounded`. The default is `Squared` since SWRDC does not take the rounded tip into account in the aerodynamic and structural calculations. Furthermore, SWRDC will not round the tip when exporting the geometry if the `Print final coordinates` option is selected, and will not display a rounded tip when `Final blade 3D` option is selected, both options which can be found in the `Plotting` panel.
- A figure illustrating the `Bluntness thickness at trailing edge` is available in section 7.3.2. Make sure the trailing edge (TE) thickness is taken into consideration when loading the airfoil profile coordinates in the `Airfoil Data` panel. SWRDC will not check whether the `Bluntness thickness at trailing edge` matches the TE thickness in the airfoil profile coordinates file. SWRDC will not crash if this aspect is neglected.
- A value between 1 and 1.2 is recommended for the `Tip factor`. Please refer to section 7.3.3 or for a more detailed description, see Brooks, Pope, and Marcolini [6].

For a detailed description of all parameters, refer to the thesis of Zhu [2].

**Noise Data**

Perform noise analysis

Surface roughness (mm)

Tower-top radius (m)  Tower-base radius (m)

Turbine hub height (m)  Shaft length (m)

Power law factor   Use built-in estimate

Turbulence length scale (m)  Set to 0 for  
Turbulence intensity  built-in calculation

Tip shape

Bluntness thickness at trailing edge (m)

Trailing edge angle (deg.)  Tip factor

Distance between tower base and observer (m)

Observer height (m)

Observer angle relative to downstream direction (deg.)

Flow is:

(see transition trigger)

Load airfoil noise database

Load reference alfa

Load reference Reynolds

Figure 18: Noise data panel.

As mentioned in section 5.11, a noise database pertaining to the airfoil specified in the **Airfoil Data** panel is necessary to perform noise analyses. The database consists of boundary layer displacement thickness values for different angles of attack and Reynolds numbers as shown in the **Load reference alfa** and **Load reference Reynolds** fields respectively.

The database is integrated into the noise analysis either by computing it before an optimization begins using the **Compute airfoil noise database before optimization?** option, or by loading an already existing database file. To load an already existing database, click **Browse** next to the **Load airfoil noise database** field. Ensure that the **Load reference alfa** and **Load reference Reynolds** fields matches accordingly with the database file. This can be checked by clicking the **Check Inputs** button. A figure such as the one shown in Figure 19 should appear and if not, the message “Input noise database file does not match reference alfa and/or Reynolds number range(s)” will be displayed in either the MS-DOS or MATLAB command windows. For the **Load reference alfa** and **Load reference Reynolds** fields, you can type the numbers manually into the text boxes or load them from a file using the **Browse** buttons. If you are typing the numbers manually, ensure to enclose

them with square brackets (i.e. []).

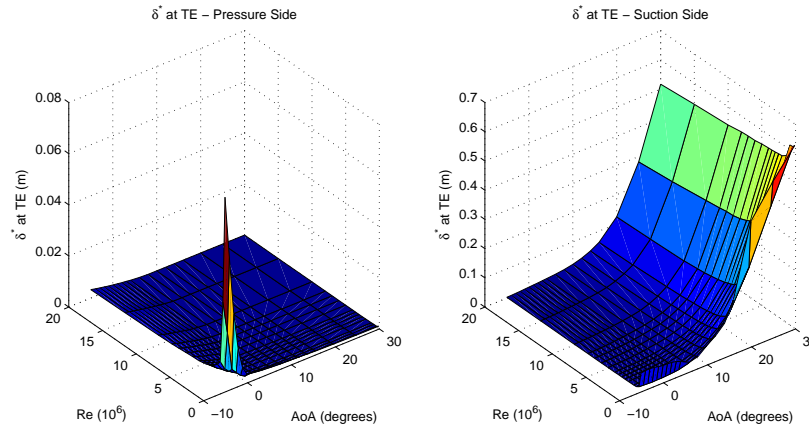


Figure 19: Boundary layer displacement thickness as a function of Reynolds number (Re) and angle of attack (AoA) for the pressure (left) and suction (right) sides of the SG6043 airfoil.

### 5.13 Objective Weight Factors

These weights allow the user to select which objectives are more important to him or her. Given a two-objective problem of maximizing  $C_P$  and minimizing starting time, if the user believes that aerodynamic efficiency is more important than starting time for his or her blade design, then the weight for  $C_P$  should be high and the weight for starting should be low (e.g.  $w_1 = 0.9$  and  $w_2 = 0.1$ ). Note the sum of the weights should be equal to one and each weight must be strictly positive. See equation (1) in section 1. Furthermore, specifying a weight of zero for any one of the objectives is the equivalent of excluding the objective from the optimization. For example, if  $w_2$  for starting time is zero, SWRDC will not attempt to minimize starting time.

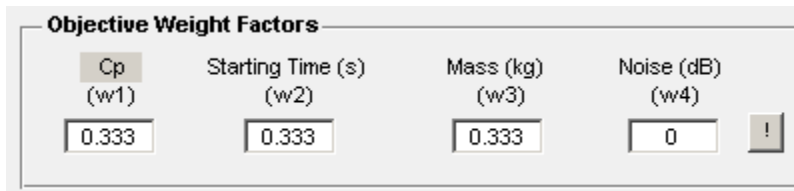


Figure 20: Objective weight factors panel.

### 5.14 Plotting

All the SWRDC plotting options are located in the **Plotting** panel. The user may select up to four plots to be displayed while the optimization is running: **Blade geometry**, **Structural performance**, **Final blade 3D** and **Optimization progress**. When the **Blade geometry** and **Structural performance** options are selected, the geometry and structural performance for each candidate blade design will be displayed. The geometry and structural performance plots will also be displayed for the baseline and final blade designs. Note that

when both of these plotting options are activated, the overall run time for the optimization may increase.

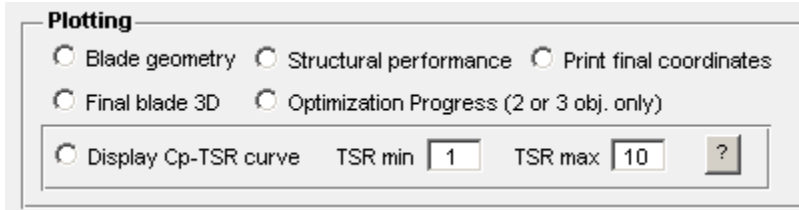


Figure 21: Plotting panel.

An example of a geometry plot is shown in Figure 22. The geometry plot contains all the relevant information about a candidate blade’s geometry as described in section 5.8. Please refer to section 5.8 for details.

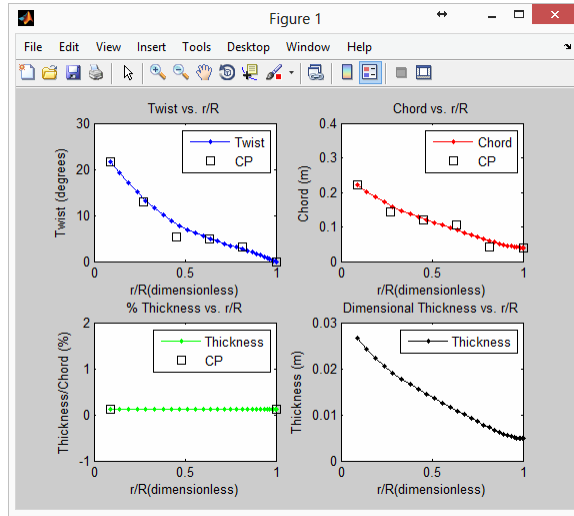


Figure 22: Blade geometry plot.

A structural performance plot is shown in Figure 23, which includes five sub-plots: shell thickness, stiffness, bending moment, deflection, and 1<sup>st</sup> flapwise eigenmode, all versus the non-dimensionalized radial position of the blade,  $r/R$ . The shell thickness plot contains the dimensional and relative thickness of the shell. The dimensional shell thickness is in metres (black line) while the relative thickness is the dimensional shell thickness divided by the chord (green line). When the **Cross-Section** option in the **Structural Data** panel is set to **Solid**, the relative shell thickness shown should be a straight horizontal line. This corresponds with the case when the shell is at the maximum thickness, thus creating a ‘Solid’ blade. If the **Structural Data** panel is set to **Hollow**, the shell thickness represents the thickness required to maintain structural integrity of the blade based on the load case entered in the **Load Case Data** panel (see section 5.7).

The stiffness plot depicts the stiffness along the first ( $EI_1$ ) and second ( $EI_2$ ) principal axes and depends strongly on the shell thickness. Since the blade cross-section is modelled as either hollow or solid, the stiffness in the edgewise direction will always be larger than in the flapwise direction. This is shown in Figure 23, where  $EI_2$  is much larger than  $EI_1$ .

The bending moments along the first ( $M1$ ) and second ( $M2$ ) principal axes, the flapwise ( $u_n$ ) and edgewise ( $u_t$ ) deflections, and the deflection shape of the first flapwise eigenmode,  $U_{y,flap1}$  and  $U_{z,flap1}$ , are included in the structural plot.

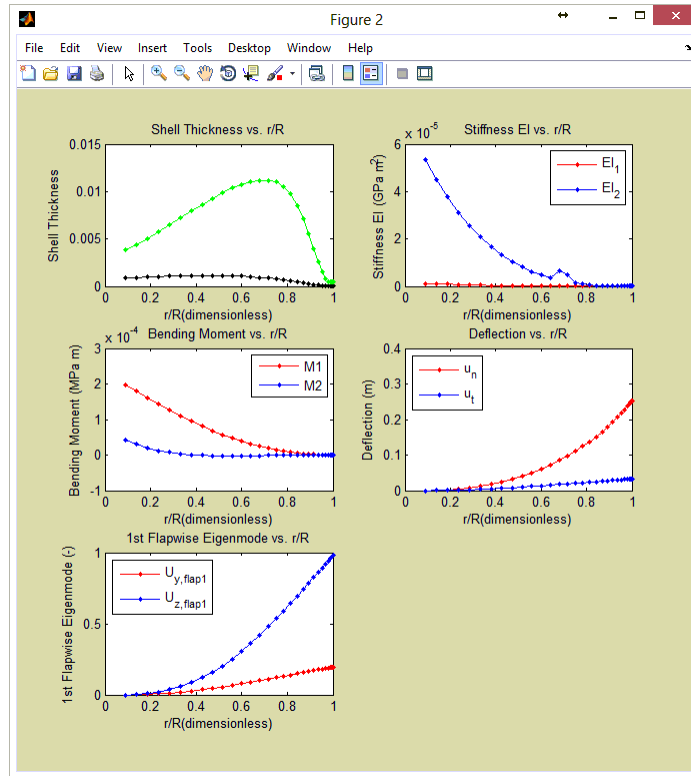


Figure 23: Structural performance plot.

If the **Final blade 3D** option is selected, a three-dimensional plot of the final blade design will appear when the optimization is finished. Figure 24 depicts such a figure.

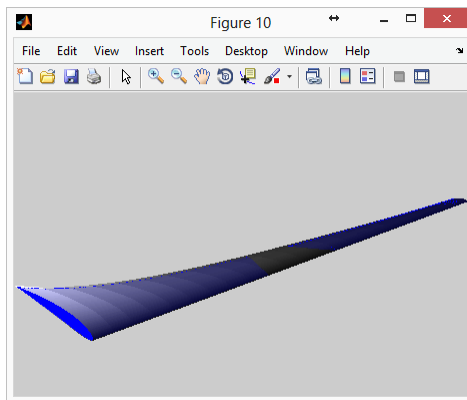


Figure 24: Final blade 3D plot.

If the **Optimization Progress** option is selected, either a three- or two-dimensional

plot will appear following each generation, displaying the objective values of the population. The best individual of the population as described in section 6.1 and the utopia point will be displayed as well, and are labelled ‘Best’ and ‘Utopia’ respectively. The utopia point holds the ideal objective value for each objective being considered, where  $C_P$  is equal to the Betz limit and Starting, Mass and Noise are equal to zero (i.e.  $C_P=0.593$  and Starting=Mass=Noise=0). The utopia point represents the best possible result for any blade design but is impossible to achieve. If the optimization is functioning properly, the best individual should approach the utopia point in the Optimization progress plot. The utopia point will only appear if the Optimize Cp instead of AEP option is deactivated. The Optimization Progress plot is only available for three- or two-objective problems.

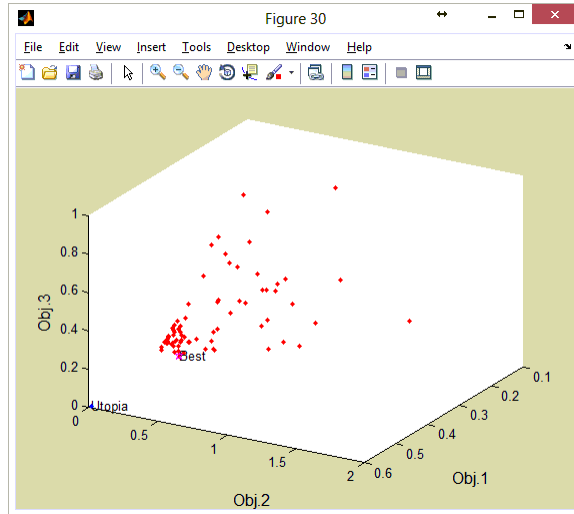


Figure 25: Optimization progress for a three-objective problem.

The last option, Display Cp-TSR curve, will write the  $C_P$  and  $C_T$  as a function of the tip-speed ratio (TSR) in the Excel results file for the baseline and final blade designs. Both curves are computed assuming the turbine is a variable-speed machine and is operating at the design windspeed for all TSRs. Figure 26 depicts the  $C_P$ -TSR and  $C_T$ -TSR curves in the Excel results file.



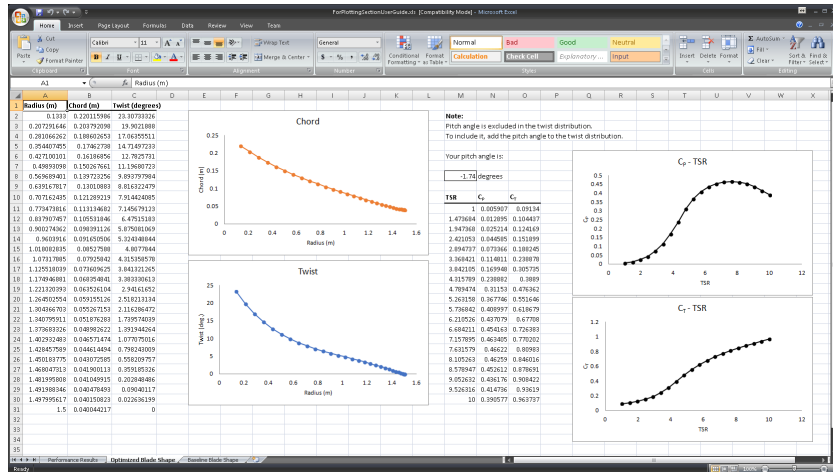


Figure 26:  $C_P$ -TSR and  $C_T$ -TSR curves displayed on the Excel results output file.

## 5.15 Parallel Computing Toolbox - MATLAB - MathWorks

The Parallel Computing Toolbox panel allows SWRDC to run in parallel and significantly reduce the overall computing time. To run SWRDC in parallel, select the Run optimization in parallel option and input an appropriate number of processors. The maximum allowable number that can be entered into the Number of processors field will be the total number of processors in your computer system or 12. The number of processors that your computer holds can be determined by viewing the Performance tab on the Windows Task Manager or typing WMIC CPU Get NumberOfLogicalProcessors /Format:List on the MS-DOS command prompt. The larger the number specified in the Number of processors field, the faster the optimization will become. If you are using MATLAB and the original source code, you must have the Parallel Computing Toolbox installed.



Figure 27: Parallel computing toolbox - MATLAB - MathWorks panel.

## 5.16 Results File

The purpose of the Results File panel is to allow the user to select the file name and location of the Excel results file. The Excel file will contain the results for the final blade design and also the baseline blade if the Run Baseline Blade option is selected on the Baseline Blade panel.

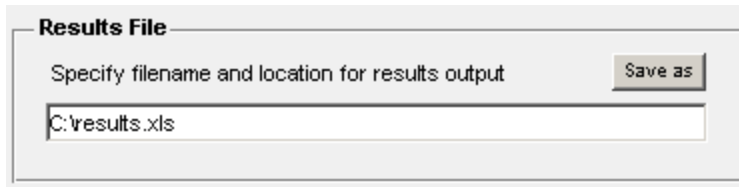


Figure 28: Results file panel.

Click the **Save as** button to display the window shown in Figure 29. Type the file name and click **Save**. The file name and location will then be displayed in the text box on the **Results File** panel.

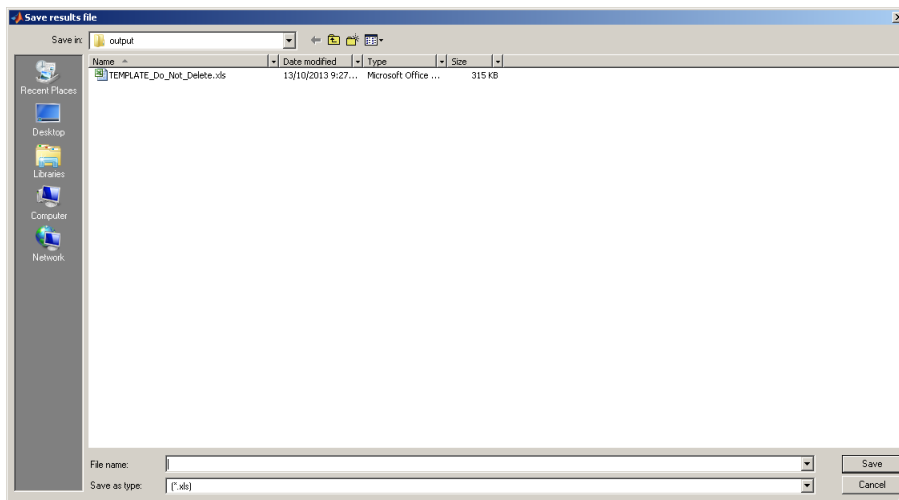


Figure 29: Saving the Excel results file.

### 5.17 Annual Energy Production (AEP)

If the **Optimize AEP instead of Cp** option on the **Annual Energy Production (AEP)** panel is enabled, SWRDC will minimize the AEP instead of the power coefficient,  $C_P$ , for the rotor/blade design. This feature can only be used if the turbine is a variable-speed machine that can operate at a single tip-speed ratio between a range of flow speeds, defined in the **Annual Energy Production (AEP)** panel as the **cut-in** and **cut-out** windspeeds.

To calculate the AEP, a probability density function to describe the flow distribution of a wind site is required. There are three probability distributions to choose from using the **---Probability type---** drop-down menu: **Rayleigh**, **Weibull**, and **User-defined**. The default is the **Rayleigh** distribution, which requires the cut-in, cut-out and mean windspeeds. If the **Weibull** distribution is selected, the user must specify the form factor,  $k$ , and the scale factor,  $A$  (m/s), instead of the mean windspeed. The last option is the **User-defined** distribution, which allows any arbitrary flow probability distribution to be used for calculating the AEP. To open a user-defined distribution, click **Browse**. The file name and location will then be displayed in the text box on the **Annual Energy Production (AEP)** panel. Note the first and last windspeed entries in the user-defined distribution must represent the cut-in and cut-out windspeeds. To visualize the input data on the **Annual Energy Production (AEP)** panel, click the **Check Inputs** button.

If the Optimize AEP instead of  $C_p$  option disabled, SWRDC will maximize the  $C_P$ . Note that optimizing a rotor/blade for maximum  $C_P$  does not necessarily create a turbine with the highest AEP.

Figure 30: Annual energy production.

### 5.18 Baseline Blade

If **Run Baseline Blade** is selected, SWRDC will calculate the baseline blade design with the file name and location specified in the text box on the **Baseline Blade** panel. The results for the baseline design will be shown on the MS-DOS (compiled) or command window (MATLAB) as described in section 6.1 as well as in the Excel results file described in section 6.3. To locate and open the desired baseline design, click the **Browse** button. The file name and location will then be displayed in the text box on the **Baseline Blade** panel. To run a test on the baseline blade using the models in SWRDC, click the **Test** button. If it fails, please review the data on the baseline blade file.

The first line on the baseline blade file must have the following three headers: radius (m), chord (m), and twist (degrees). The data below the headers must match the dimensions given in the headers (i.e. meters, meters, and degrees respectively). Any number of rows is allowed for the blade data, but it must include the radius, chord and twist at the root and tip of the blade. An example is shown in Figure 32, where the hub and rotor radii are equal to 0.1333 and 1.5 meters respectively.

Figure 31: Baseline blade.

radius(m)	chord(m)	twist(deg)
0.1333	0.2502	24.21
0.2325	0.2318	21.06
0.2975	0.1998	15.87
0.3625	0.1732	11.92
0.4275	0.1512	8.96
0.4925	0.1333	6.77
0.5575	0.1186	5.18
0.6225	0.1067	4.02
0.6875	0.0971	3.16
0.7525	0.0892	2.49
0.8175	0.0826	1.93
0.8825	0.0771	1.44
0.9475	0.0723	0.99
1.0125	0.0680	0.59
1.0775	0.0641	0.25
1.1425	0.0604	-0.06
1.2075	0.0570	-0.36
1.2725	0.0538	-0.67
1.3375	0.0508	-0.98
1.4025	0.0484	-1.28
1.4675	0.0466	-1.59
1.5000	0.0460	-1.74

Figure 32: Example of blade data used as a baseline.

## 5.19 Saving and Loading GUI Settings

GUI settings for SWRDC can be saved or loaded using this panel. To save the data stored in the GUI, click **Save GUI settings**. The GUI settings must be stored as a MATLAB figure file (\*.fig). To load GUI settings from a previous session, click **Load GUI settings**. When loading, the GUI will close (and all data on it will be lost) and a new one will appear with the settings you have loaded.

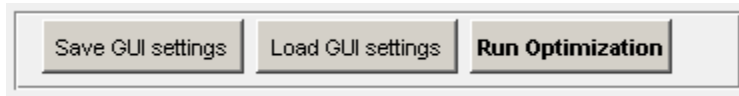


Figure 33: Saving and loading GUI settings.

## 6 Running an Optimization

### 6.1 Clicking the Run Optimization button

Once all settings on the GUI have been applied, the optimization can be executed by clicking on the **Run Optimization** button shown in Figure 33. If you are running SWRDC on the compiled version, information relating to the optimization and its progress will be displayed on the MS-DOS window as shown in Figure 34. If you are using MATLAB and the original source code, the information will be displayed on the command window.

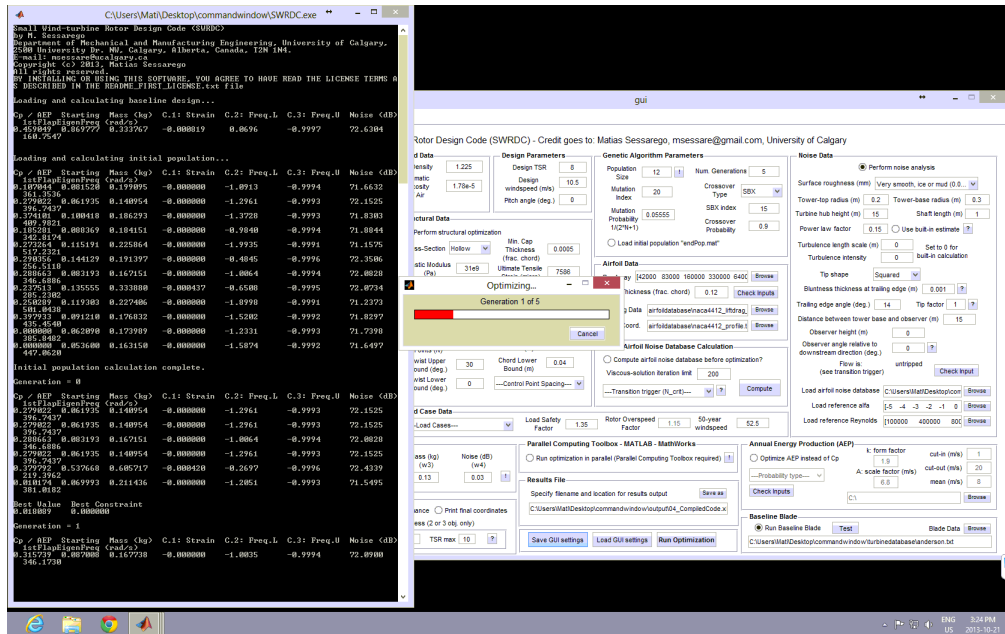


Figure 34: Running the optimization.

The program begins by displaying basic information about SWRDC and a disclaimer that `README.FIRST_LICENSE.txt` must be read before installing or using SWRDC.

```

Small Wind-turbine Rotor Design Code (SWRDC)
by M. Sessarego
Department of Mechanical and Manufacturing Engineering,
University of Calgary,
2500 University Dr. NW, Calgary, Alberta, Canada, T2N 1N4.
E-mail: msessare@ucalgary.ca
Copyright (c) 2013, Matias Sessarego
All rights reserved.
BY INSTALLING OR USING THIS SOFTWARE, YOU AGREE TO HAVE READ THE
LICENSE TERMS AS DESCRIBED IN THE README_FIRST_LICENSE.txt file

```

If the Run Baseline Blade option in the Baseline Blade panel is selected, SWRDC will calculate the baseline blade design and display the results as shown below:

Loading and calculating baseline design...

```

Cp / AEP Starting Mass (kg) C.1: Strain C.2: Freq.L C.3: Freq.U Noise (dB) 1stFlapEigenFreq (rad/s)
0.459049 0.869777 0.333767 -0.000819 0.0696 -0.9997 72.6304 160.7547

```

For explanations of each heading, for example Cp / AEP, please refer to section 6.2. A random initial population of candidate blade designs will then start to generate. The size of the initial population will be equal to the number specified in the Population Size field in the Genetic Algorithm Parameters panel. If the Load initial population “endPop.mat” option in the Genetic Algorithm Parameters panel is selected, the population stored in the “endPop.mat” file will be generated instead.

Loading and calculating initial population...

Cp / AEP	Starting	Mass (kg)	C.1: Strain	C.2: Freq.L	C.3: Freq.U	Noise (dB)	1stFlapEigenFreq (rad/s)
0.107044	0.081520	0.199095	-0.000000	-1.0913	-0.9994	71.6632	361.3536
0.279022	0.061935	0.140954	-0.000000	-1.2961	-0.9993	72.1525	396.7437
0.374101	0.100418	0.186293	-0.000000	-1.3728	-0.9993	71.8303	409.9821
0.185281	0.088369	0.184151	-0.000000	-0.9840	-0.9994	71.8844	342.8174
0.273264	0.115191	0.225864	-0.000000	-1.9935	-0.9991	71.1575	517.2321
0.290356	0.144129	0.191397	-0.000000	-0.4845	-0.9996	72.3506	256.5118
0.288663	0.083193	0.167151	-0.000000	-1.0064	-0.9994	72.0828	346.6886
0.237513	0.135555	0.333880	-0.000437	-0.6508	-0.9995	72.0734	285.2302
0.250289	0.119303	0.227406	-0.000000	-1.8998	-0.9991	71.2373	501.0438
0.397933	0.091210	0.176832	-0.000000	-1.5202	-0.9992	71.8297	435.4540
0.000000	0.062090	0.173989	-0.000000	-1.2331	-0.9993	71.7398	385.8482

Once the initial population is finished calculating, “Initial population calculation complete” will appear followed by “Generation = 0”. The zero value indicates that the first iteration has begun and will not finish until “Generation = 1” appears. Each iteration represents a generation of children, which will be half the Population Size. Consequently, each iteration involves only half the computing cost required for generating the initial population.

Initial population calculation complete.

Generation = 0

Cp / AEP	Starting	Mass (kg)	C.1: Strain	C.2: Freq.L	C.3: Freq.U	Noise (dB)	1stFlapEigenFreq (rad/s)
0.279022	0.061935	0.140954	-0.000000	-1.2961	-0.9993	72.1525	396.7437
0.279022	0.061935	0.140954	-0.000000	-1.2961	-0.9993	72.1525	396.7437
0.288663	0.083193	0.167151	-0.000000	-1.0064	-0.9994	72.0828	346.6886
0.279022	0.061935	0.140954	-0.000000	-1.2961	-0.9993	72.1525	396.7437
0.379792	0.537668	0.605717	-0.000420	-0.2697	-0.9996	72.4339	219.3962
0.010174	0.069993	0.211436	-0.000000	-1.2051	-0.9993	71.5495	381.0182

The last step for each iteration is to determine the best individual of the current population. The best individual is determined by selecting the individual with the smallest value for equation (1) and that does not violate the constraints. The value for equation (1) of the best individual is displayed in the **Best Value** field. The overall constraint violation is calculated following a scheme described in Deb [3] and takes priority over the value obtained for equation (1) when selecting the best individual. The overall constraint violation of the best individual is displayed in the **Best Constraint** field. A value of zero for **Best Constraint** indicates that the blade does not violate any constraint. Once “Generation = 1” appears, the first iteration is complete and the subsequent iteration will begin.

Best Value Best Constraint  
0.018089 0.000000

Generation = 1

Cp / AEP	Starting	Mass (kg)	C.1: Strain	C.2: Freq.L	C.3: Freq.U	Noise (dB)	1stFlapEigenFreq (rad/s)
0.315739	0.087008	0.167738	-0.000000	-1.0035	-0.9994	72.0900	346.1730
0.288663	0.083193	0.167151	-0.000000	-1.0064	-0.9994	72.0828	346.6886
0.252418	0.091470	0.137815	-0.000000	-0.5597	-0.9995	72.4531	269.5001
0.223395	0.064960	0.186170	-0.000000	-1.6189	-0.9992	71.7000	452.5113
0.288663	0.083193	0.167151	-0.000000	-1.0064	-0.9994	72.0828	346.6886
0.286601	0.086778	0.178085	-0.000000	-1.0417	-0.9994	72.0823	352.7858

During the optimization, a wait bar will display the optimization’s progress by filling a bar with red from left to right. To abort the optimization, click “Cancel” on the wait bar. The optimization will be aborted once the current iteration (or generation) is finished calculating. Depending on the Population Size chosen and the point where the cancel button was pressed, it may take several minutes or hours before the iteration is complete.

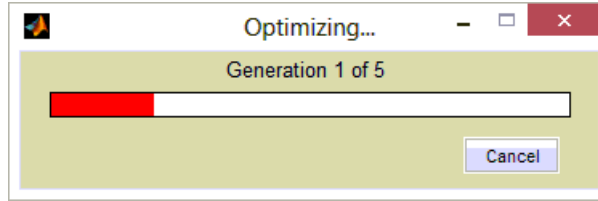


Figure 6.1 illustrates what occurs after the cancel button on the wait bar is pressed or when the maximum number of generations specified in the Num. Generations field in the Genetic Algorithm Parameters panel is reached. For the example optimization shown below, the maximum number of generations is five. After Generation = 5 is displayed, the last best individual recorded becomes the final blade design. The final blade design is re-evaluated in order to display its optimum performance with respect to the objectives and constraints: Cp / AEP, starting, mass, strain, etc. For this particular example, the final design has the following: Cp=0.321, Starting=0.091, Mass=0.178, C.1: Strain=0,...,1stFlapEigenFreq=353.580.

```

Generation = 4

Cp / AEP  Starting  Mass (kg)  C.1: Strain  C.2: Freq.L  C.3: Freq.U  Noise (dB)  1stFlapEigenFreq (rad/s)
0.315739  0.087008  0.167738  -0.000000  -1.0035      -0.9994      72.0900     346.1730
0.301467  0.083098  0.167276  -0.000000  -1.0109      -0.9994      72.0627     347.4589
0.288259  0.081900  0.180956  -0.000000  -1.1479      -0.9994      72.0242     371.1360
0.328710  0.090543  0.181293  -0.000000  -1.1013      -0.9994      72.0601     363.0723
0.294540  0.083539  0.166939  -0.000000  -1.0077      -0.9994      72.0858     346.9139
0.312908  0.086602  0.167713  -0.000000  -1.0034      -0.9994      72.0892     346.1557

Best Value  Best Constraint
0.129188    0.000000

Generation = 5

Cp / AEP  Starting  Mass (kg)  C.1: Strain  C.2: Freq.L  C.3: Freq.U  Noise (dB)  1stFlapEigenFreq (rad/s)
0.321426  0.090892  0.178067  -0.000000  -1.0463      -0.9994      72.0920     353.5791

FINISHED

```

SWRDC will then record the results of the final blade design into an Excel file. The recording takes a few minutes to complete; please be patient and wait until “FINISHED” appears before opening or manipulating the Excel results file. For details regarding the Excel file and the outputs from SWRDC, refer to section 6.3.

## 6.2 Optimization Headings

The headings are as follows: Cp / AEP, Starting, Mass (kg), C.1: Strain, C.2: Freq.L, C.3: Freq.U, Noise (dB), and 1stFlapEigenFreq (rad/s). Each quantity is calculated for all candidate blade designs, the baseline design if provided, and the final optimum design. The example shown in Figure 6.2 will be used to explain some of the headings.

```

Cp / AEP  Starting  Mass (kg)  C.1: Strain  C.2: Freq.L  C.3: Freq.U  Noise (dB)  1stFlapEigenFreq (rad/s)
Max Strain at Max Thickness Exceeded
0.379376  1.690377  1.696081  0.049374    0.1072      -0.9997      71.8067     154.2667

```

### 1. Cp / AEP

The power coefficient is displayed here and must be between 0 and 0.59. If zero is displayed, this signifies that the BEM algorithm was unable to converge to a feasible solution. If the Optimize AEP instead of Cp option is selected in the Annual Energy Production (AEP) panel, the number shown will represent the AEP in kWh/year.

2. Starting  
Starting time is displayed here and should be treated as a relative quantity. If a starting time of 701, 901, or 1101 is shown, this signifies that the candidate blade is unable to start. If **Perform starting analysis** in the **Starting Data** panel is not selected, starting time will be displayed as “NaN” for all blades to indicate that starting is excluded from the optimization.
3. Mass (kg)  
Blade mass is displayed here in kilograms regardless of whether or not the **Perform structural optimization** option in the **Structural Data** panel is selected.
4. C.1: Strain  
The first constraint (C.1) represents the maximum value of strain along the blade’s length that must be below the maximum allowable strain as determined by the **Ultimate Tensile Strain** and **Material Safety Factor** fields in the **Structural Data** panel. A number equal to zero or below signifies that the strain constraint is satisfied. A positive value under this heading signifies that the candidate blade is structurally infeasible and is accompanied by the message “Max Strain at Max Thickness Exceeded” as shown in Figure 6.2, where the value of C.1: Strain is 0.049374.
5. C.2: Freq.L  
The second constraint (C.2) represents the amount which the 1<sup>st</sup> flapwise eigenfrequency of the blade differs from the acceptable lower bound. A negative quantity or a value of zero indicates that the lower bound is met. Otherwise, the lower bound is violated. In Figure 6.2, the lower bound is violated since a value of 0.1072 appears under the C.2: Freq.L heading.
6. C.3: Freq.U  
The third constraint (C.3) represents the amount which the 1<sup>st</sup> flapwise eigenfrequency of the blade differs from the acceptable upper bound. A negative quantity or a value of zero indicates that the upper bound is met. Otherwise, the upper bound is violated. In Figure 6.2, the upper bound is met since a value of -0.9997 appears under the C.3: Freq.U heading.
7. Noise (dB)  
Noise emitted by the blade is displayed here in decibels (dB). If **Perform noise analysis** in the **Noise Data** panel is not selected, noise will be displayed as “NaN” for all blades to indicate that noise is excluded from the optimization.
8. 1stFlapEigenFreq (rad/s)  
The 1<sup>st</sup> flapwise eigenfrequency of the blade is displayed here in radians per second (rad/s).

### 6.3 Optimization Finished: Analysing the Outputs

When the optimization is finished, the word “FINISHED” should appear on the bottom of the MS-DOS window (compiled) or on the bottom of the command window (MATLAB) as shown in Figure 35.



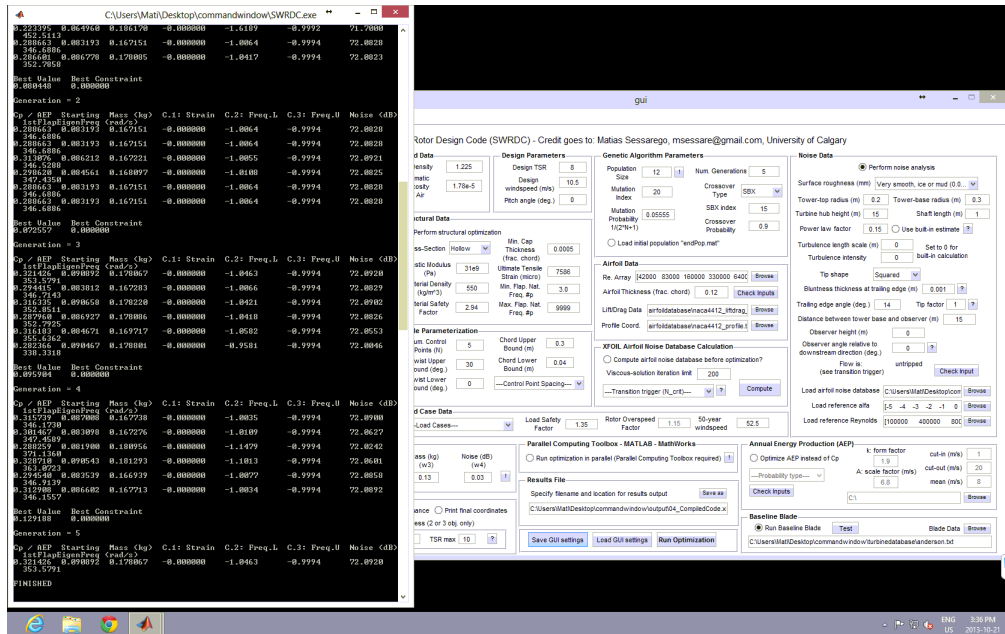


Figure 35: Optimization finished.

The Excel file containing the results of the final blade design should be located in the directory specified in the GUI prior to running the optimization. There are three sheets in the Excel file, namely: Performance Results, Optimized Blade Shape, and Baseline Blade Shape.

In the Performance Results sheet, the performance of the optimized and baseline (if selected) blades will be displayed, specifically: power coefficient / AEP, power, torque, thrust, flapwise root-bending moment, starting time, blade mass, strain violation, frequency violation 1 and 2, 1<sup>st</sup> flapwise eigenfrequency, and noise. In addition, a summary of the turbine input data will be shown. If a baseline blade was provided and the optimization was performed correctly, then the overall results for the optimized blade shown on the Performance Results sheet should be better than the baseline design. If this is not the case, it may be necessary to adjust the parameters in the Genetic Algorithm Parameters panel such as increasing the number of generations or the population size, in order to achieve a better result.

In the optimized and baseline blade shape sheets are the chord and twist distributions, pitch angle, and the  $C_p$ -TSR curves if the Display  $C_p$ -TSR curve option is selected. Note the  $C_p$ -TSR curves are computed assuming the turbine is a variable-speed machine and is operating at the design windspeed for all TSRs.

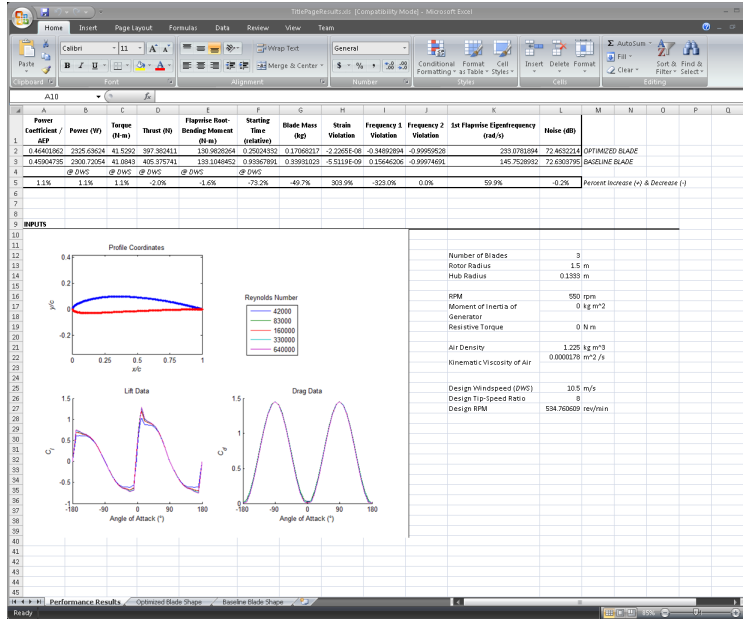


Figure 36: Excel results file showing the Performance Results sheet.

## 7 Notes on GUI Inputs

The GUI includes push buttons with question or exclamation marks to assist the user in selecting the appropriate settings. These push buttons generate messages or images, which are summarized in this section.

### 7.1 Objective Weight Factors

Note:  $w_1 + w_2 + \dots = 1$

### 7.2 Genetic Algorithm Data: Population Size

Population size must be even when divided by 2.

### 7.3 Noise Data

#### 7.3.1 Power Law Factor

The mean wind speed varies with height and it's often described with power law relationship:

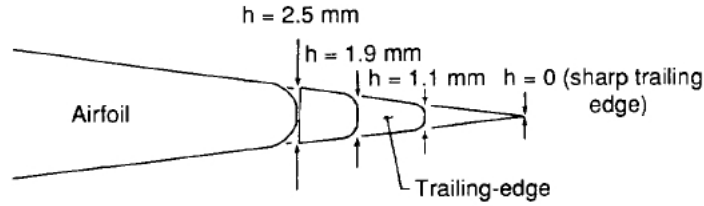
$$V_z = V_{ref} \left( \frac{Z}{Z_{ref}} \right)^\gamma$$

where  $\gamma$  is the power law factor which gives the amount of shear, typically between 0.1 and 0.25. Instead of specifying the value of the power law factor, you can use the built-in estimate using the expression by Counihan (1975):

$$\gamma = 0.24 + 0.096 \log_{10} z_o + 0.016(\log_{10} z_o)^2$$

where  $z_o$  is the surface roughness.

### 7.3.2 Bluntness Thickness at Trailing Edge



### 7.3.3 Tip Factor

The tip vortex formation noise spectrum in a 1/3-octave presentation is predicted by:

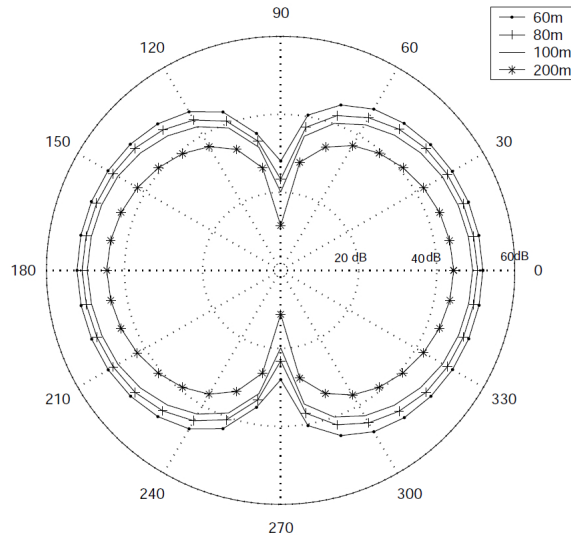
$$\text{SPL}_{\text{TIP}} = 10 \log \left( \frac{M^2 M_{\text{max}}^3 l^2 \bar{D}_h}{r_e^2} \right) - 30.5 (\log St'' + 0.3)^2 + 126.$$

The spanwise extent at the trailing-edge of the separation due to the tip vortex,  $l$ , depends on the angle of attack of the tip,  $\alpha_{\text{TIP}}$ .  $\alpha_{\text{TIP}}$  must be redefined according to computed sectional loading if the blade has a small aspect ratio, is twisted, or encounters non-uniform flow over its span. Since a wind-turbine blade normally possesses some these characteristics,  $\alpha_{\text{TIP}}$  should be corrected. The redefined  $\alpha'_{\text{TIP}}$  is:

$$\alpha'_{\text{TIP}} = \left[ \left( \frac{\partial L' / \partial y}{(\partial L' / \partial y)_{\text{ref}}} \right)_{y \rightarrow \text{TIP}} \right] \alpha_{\text{TIP}}$$

where the term within the square brackets is referred to as the tip factor and is typically between 1 and 1.2.

### 7.3.4 Sound Pressure Level at Different Observer Positions



Sound pressure level at different observer positions.

## 7.4 XFOIL Airfoil Noise Database Calculation: Transition Criterion

Transition in an XFOIL solution is triggered by one of two ways:

1. free transition:  $e^N$  criterion is met;
2. forced transition: a trip or the trailing edge is encountered.

The  $e^N$  method is always active, and free transition can occur upstream of the trip. The  $e^N$  method has the user-specified parameter  $N_{crit}$ , which is the log of the amplification factor of the most-amplified frequency which triggers transition. A suitable value of this parameter depends on the ambient disturbance level in which the airfoil operates, and mimics the effect of such disturbances on transition. Below are typical values of  $N_{crit}$  for various situations.

situation	$N_{crit}$
sailplane	12-14
motorglider	11-13
clean wind tunnel	10-12
average wind tunnel	9
dirty wind tunnel	4-8

## 8 Building a CAD File using SolidWorks

This section will demonstrate how the coordinates from SWRDC are imported in a computer-aided design (CAD) program such as SolidWorks. Once the blade is imported into SolidWorks, you can use the CAD file to build the blade on a rapid-prototyping machine or a computer numerical control (CNC) milling machine, for example. SolidWorks 2012 x64 Student Edition on a Windows 7 operating system will be used to demonstrate the procedure.

1. The first step is to open SolidWorks. An interface such as the one shown in Figure 37 should appear.

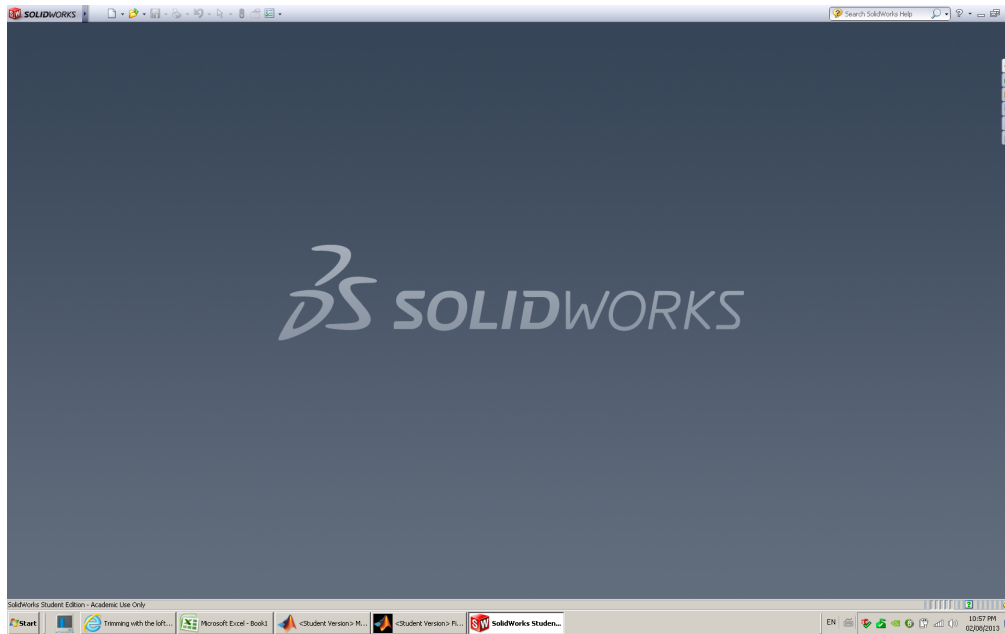


Figure 37: 1

2. Click on File → New, select Part: a 3D representation of a single design component and click OK.

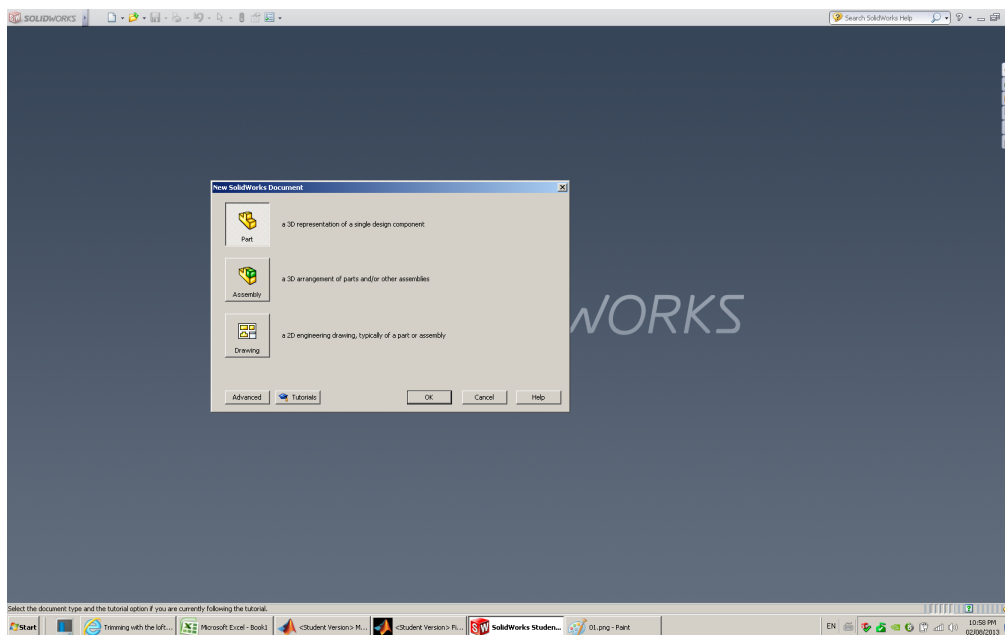


Figure 38: 1

3. On the Features tab, click Curves and select Curve Through XYZ Points.

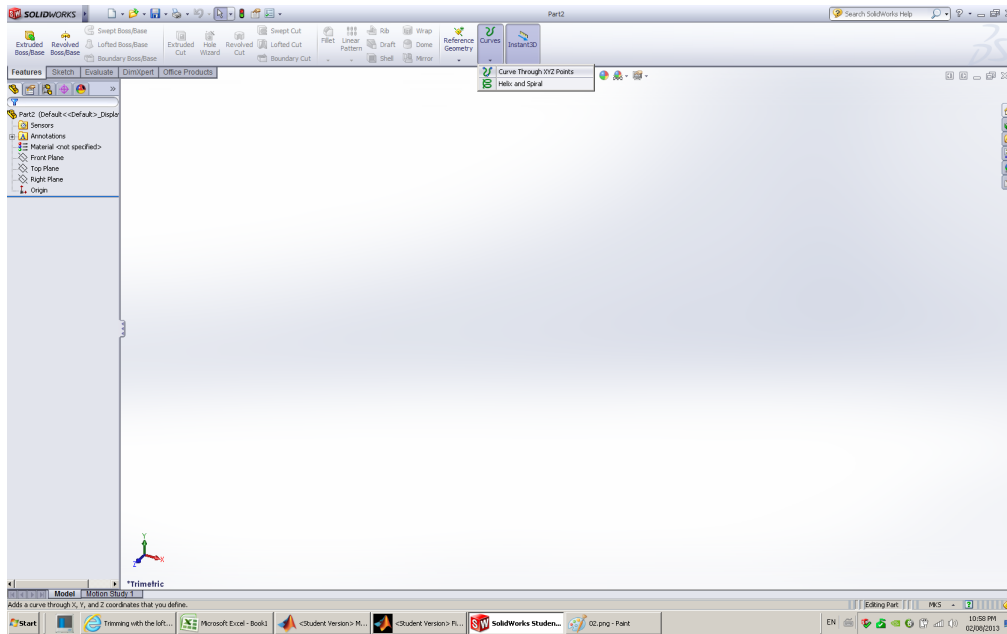


Figure 39: 1

4. Click **Browse** and find the *exportedcoords* folder where the coordinates from the optimization are located. Make sure Text Files (\*.txt) is selected on the drop-down menu above the Open and Cancel buttons. Begin by opening the *pro\_coords1.txt* file, which represents the X-Y-Z coordinates of the outer profile for the first blade element.

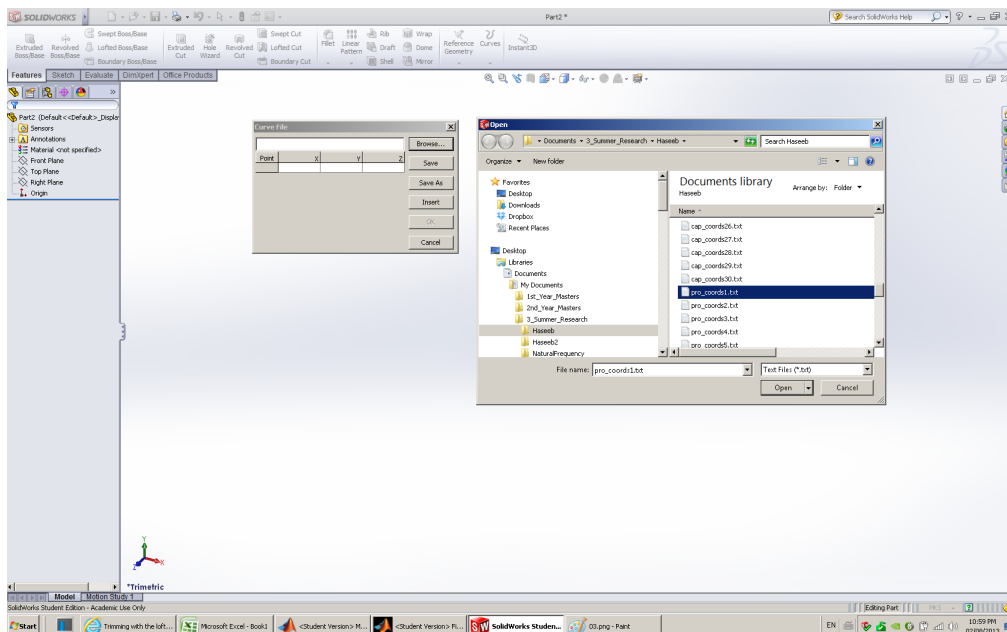


Figure 40: 1

- The X-Y-Z coordinates will be displayed on a table. The X, Y, and Z coordinates correspond to the horizontal, vertical and longitudinal directions of the blade element respectively and are measured in metres (m). The X-direction is aligned with the airfoil profile's chord line, while the Z-direction is aligned with the blade length. The Y-direction points towards the airfoil profile's upper surface. Click OK to import the coordinates.

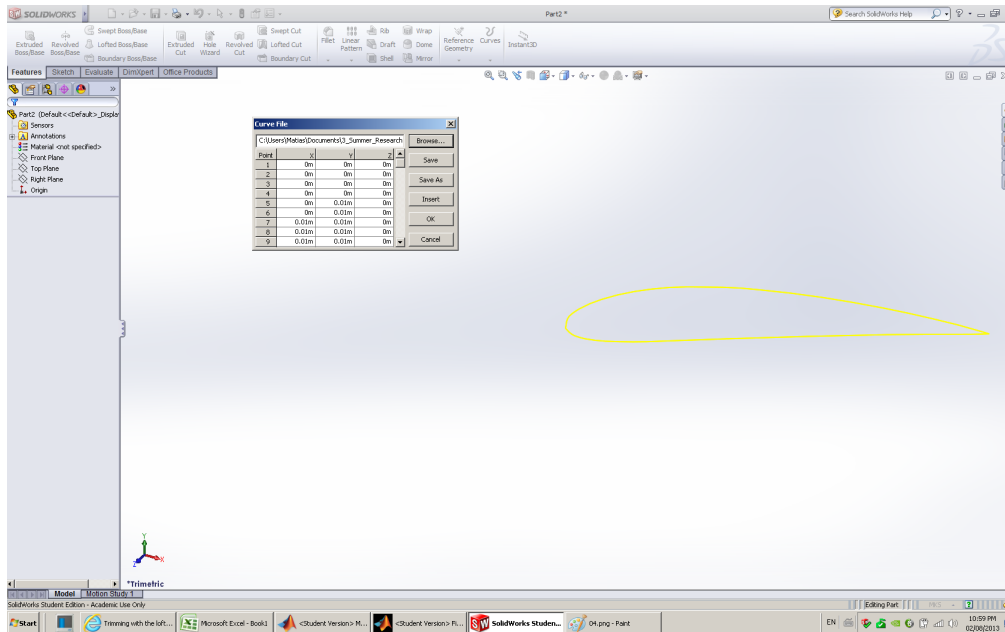


Figure 41: 1

- Place a reference plane by clicking **Reference Geometry** → **Plane** and select the airfoil as the first reference. Click on the green check mark to accept.

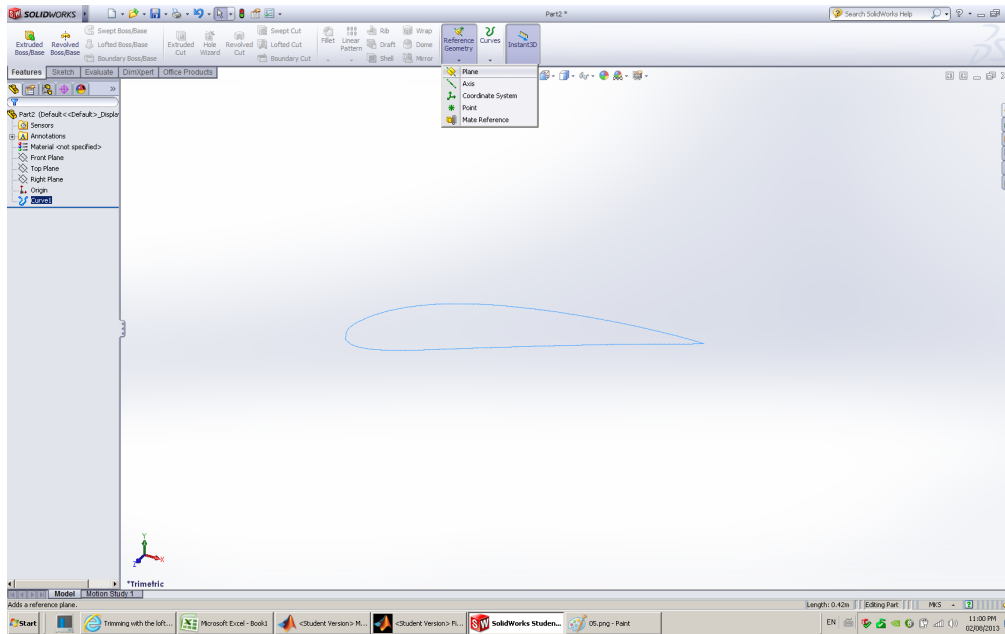


Figure 42: 1

7. The airfoil should be embedded on a reference plane as shown in Figure 43.

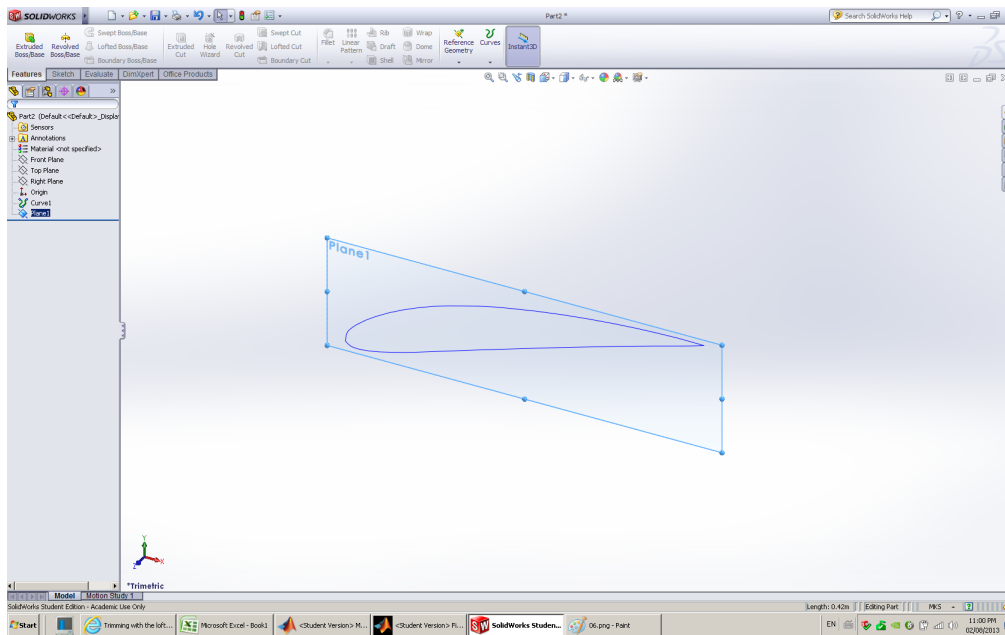


Figure 43: 1

8. On the Sketch tab, click Sketch and select the plane that coincides with the airfoil profile.



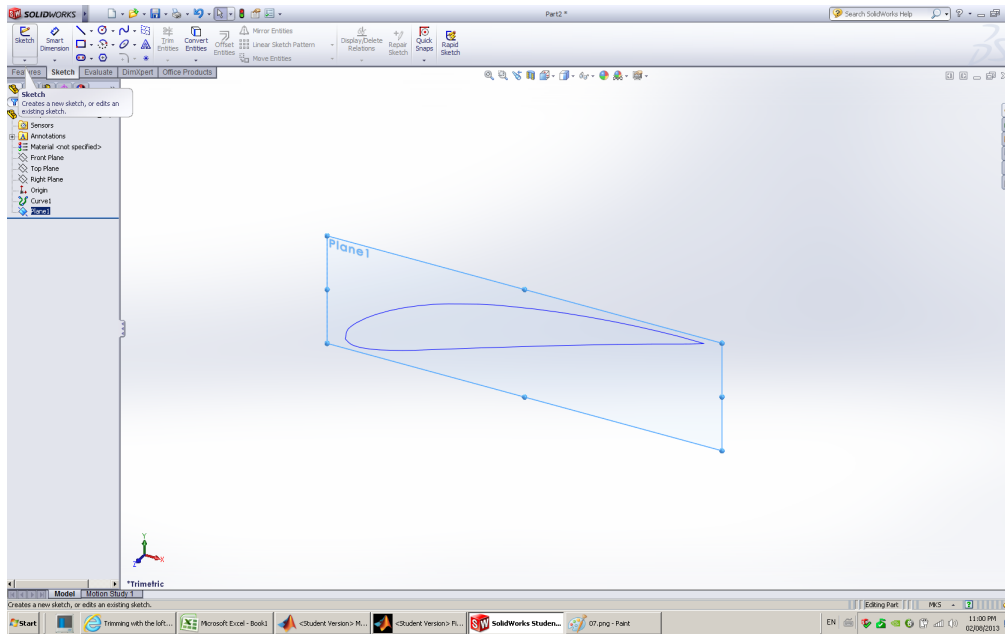


Figure 44: 1

9. The plane with the airfoil should be displayed in a frontal view as shown in Figure 45.

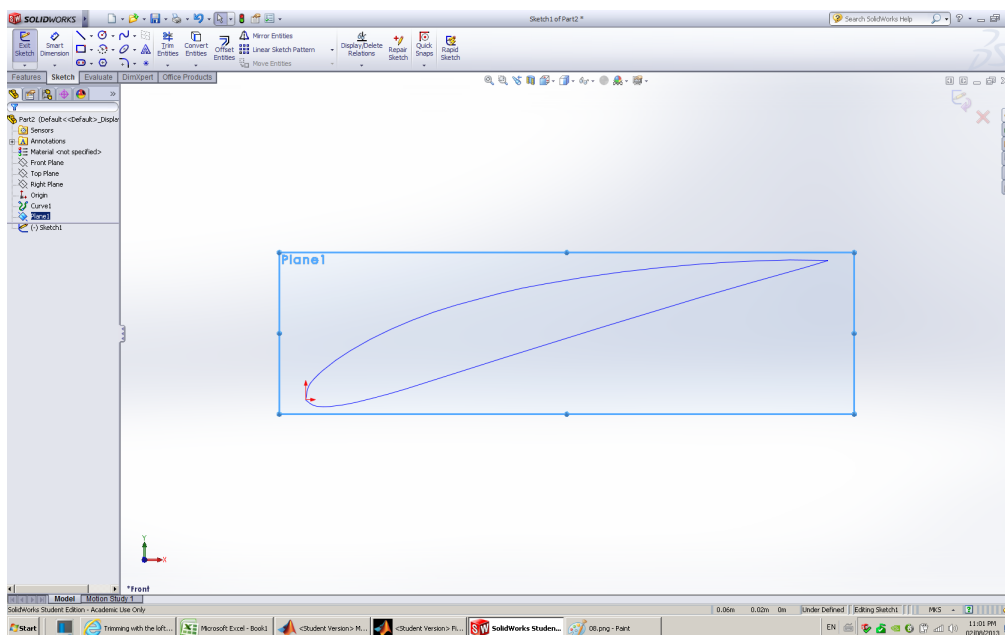


Figure 45: 1

10. Click on **Convert Entities** and select the airfoil profile. A text that reads **Edge<1>** should appear under the **Entities to Convert** field. Click on the green check mark

to accept. The airfoil profile should then appear as a thick black line as opposed to a light blue colour. Exit the sketch.

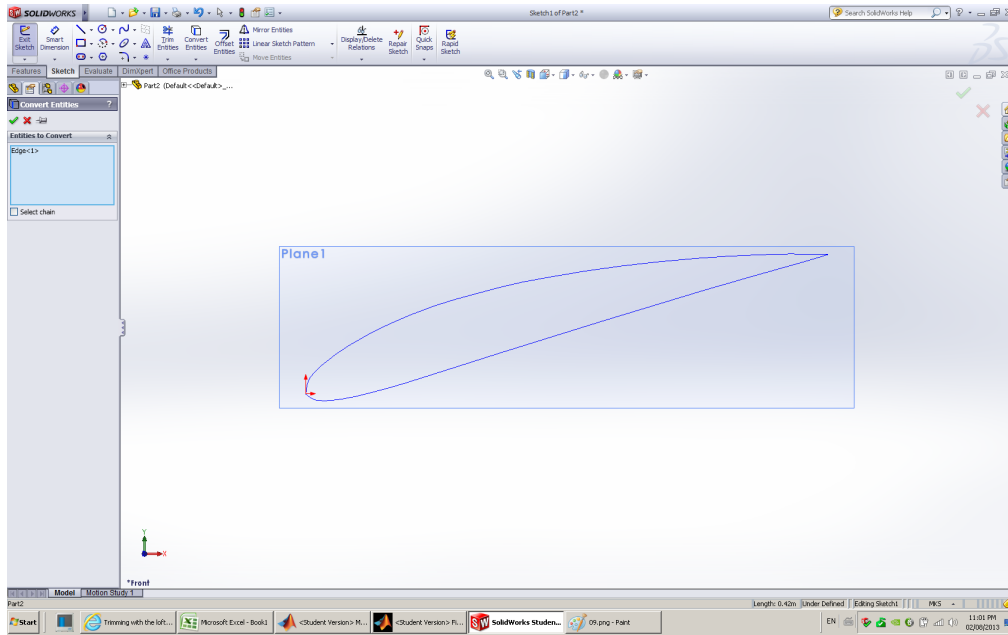


Figure 46: 1

11. The outer profile coordinates have been imported and converted as a sketch. Select **Curve Through XYZ Points** after clicking the **Curves** button on the **Features** tab. Open the inner coordinates for the first blade element by selecting the `cap_coords1.txt` file. If the blade was modelled as a solid in the optimization, ignore steps 11 and 12.

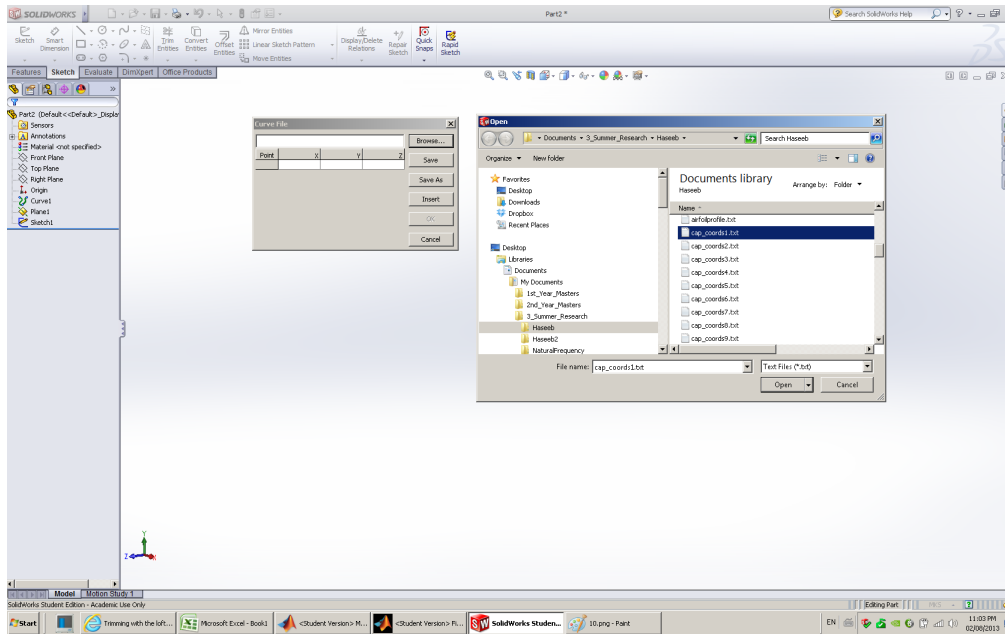


Figure 47: 1

- Click on the plane where the outer airfoil profile is situated. Click **Sketch** on the **Sketch** tab. Convert the inner profile to a sketch by repeating step 10. The first blade element is complete.

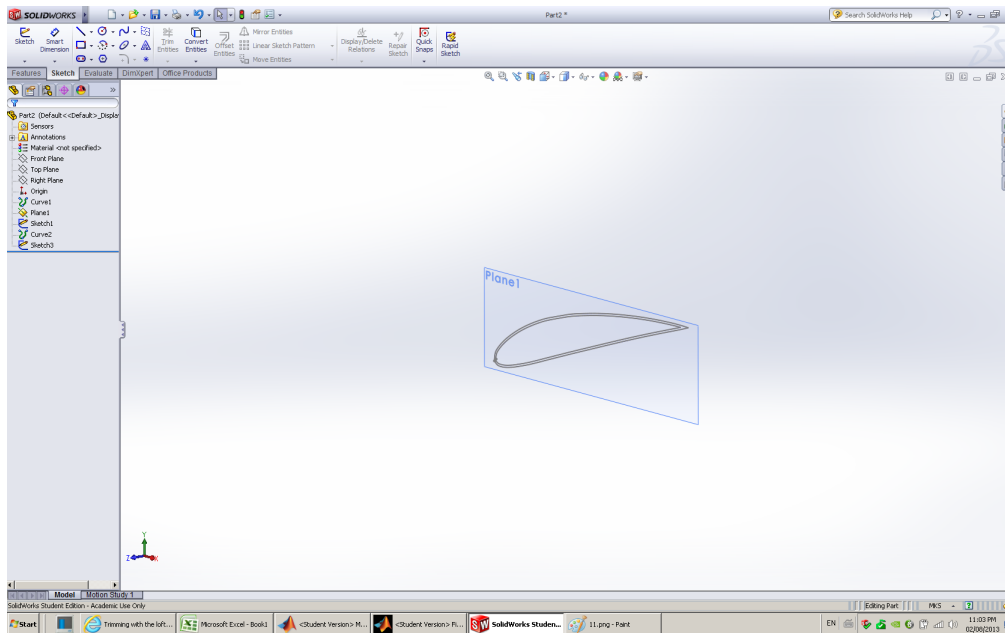


Figure 48: 1

- Place the second blade element by repeating steps 3-12 using the `pro.coords2.txt`

and cap\_coords2.txt files. The interface should display two blade cross-sections as shown in Figure 49.

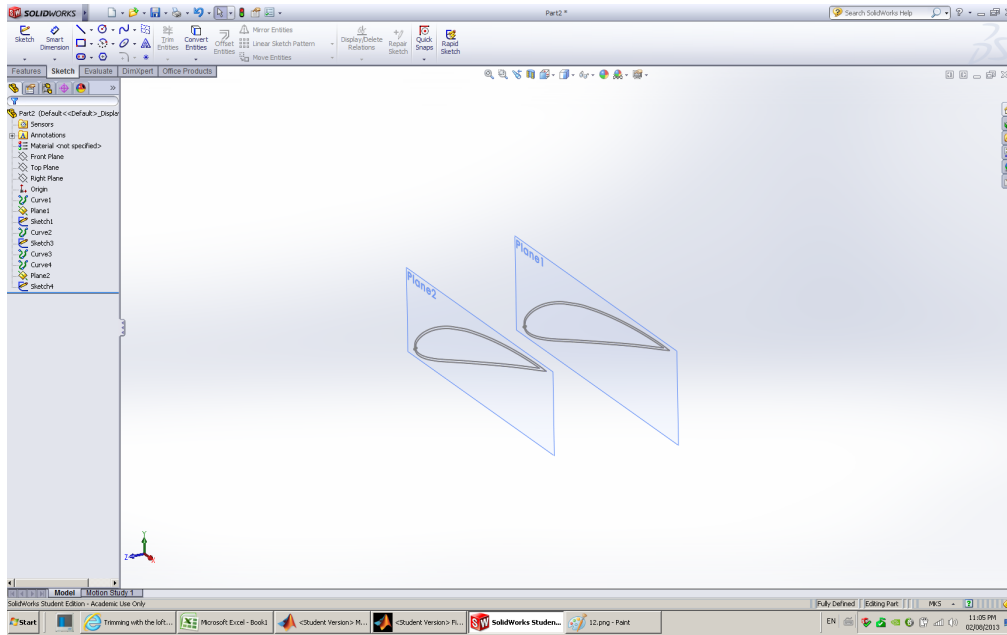


Figure 49: 1

14. Create a guide curve by clicking **Curves** on the **Features** tab and selecting **Curve Through Reference Points**. To create the guide curve, select the reference points on the leading edges of each airfoil and click on the green check mark to accept. Click **Loft Boss/Base** on the **Features** tab and select the outer profiles for the **Profiles** field and the guide curve for the **Guide Curves** field. Click on the green check mark to accept.

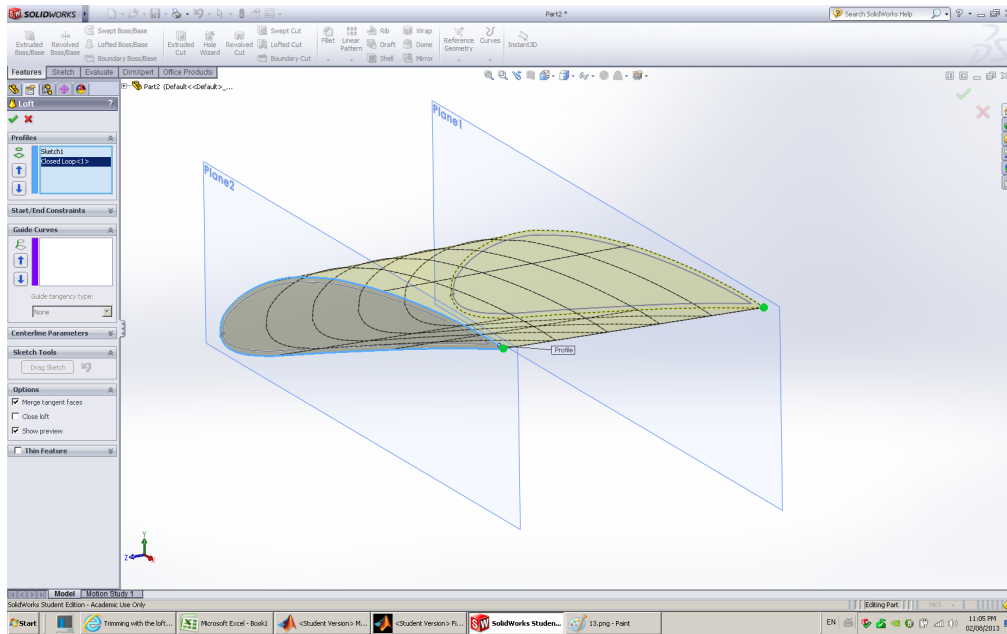


Figure 50: 1

15. A solid portion of the blade should appear as shown in Figure 51. If the blade was modelled as solid in the optimization, repeat steps 3-15 for all blade elements and skip steps 16 and 17. Once all blade elements are taken into account, the CAD file is ready for fabrication.

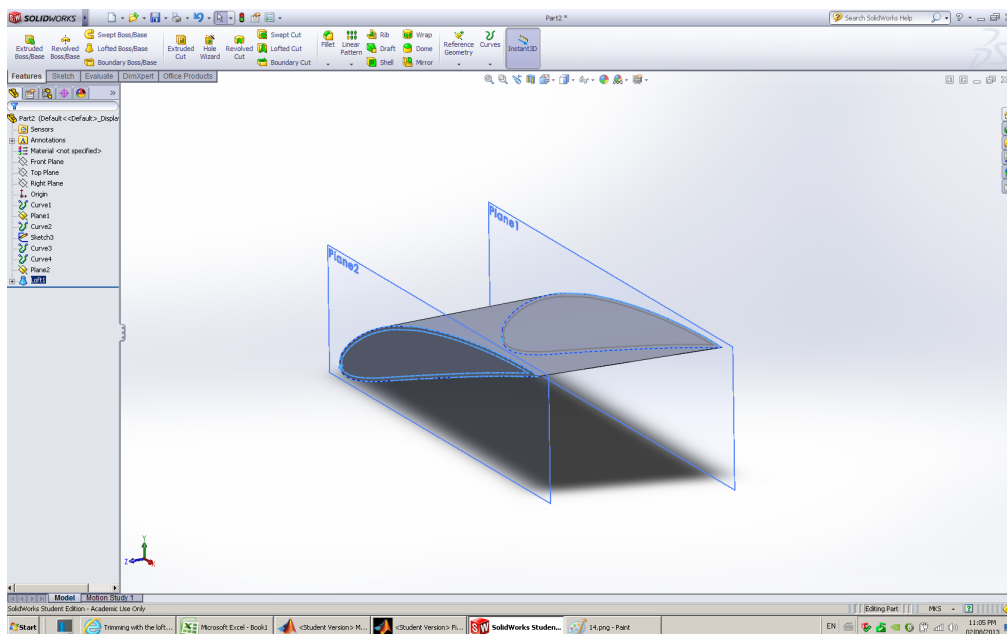


Figure 51: 1

16. To model a hollow blade, click **Lofted-Cut** on the **Features** tab and select the inner profiles by clicking on their reference points for the **Profiles** field. If necessary, create a guide curve using the reference points on the inner profiles. Click on the green check mark to accept.

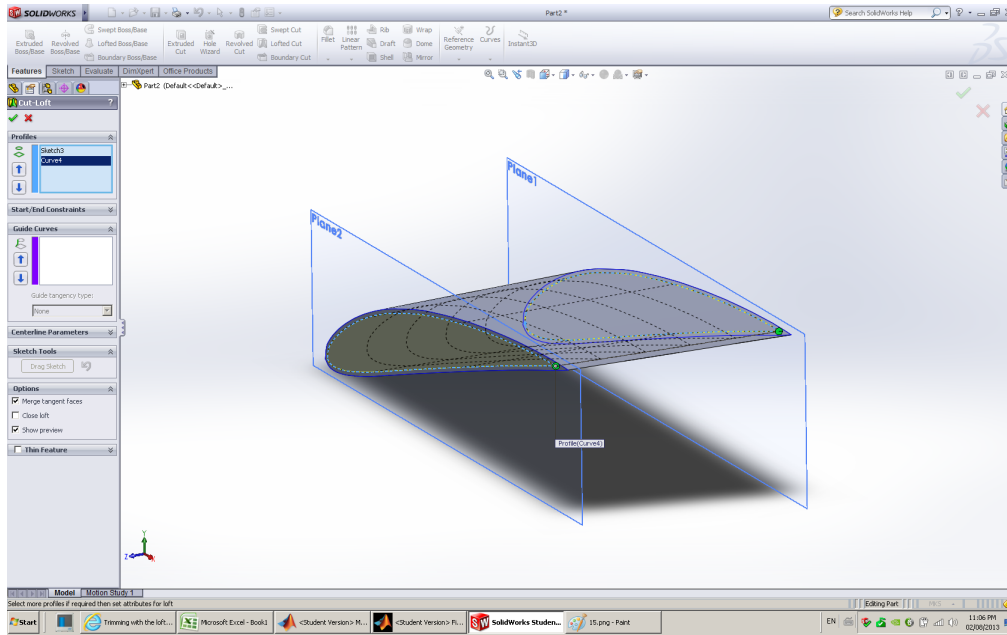


Figure 52: 1

17. A hollow portion of the blade should appear as shown in Figure 53. Repeat steps 3-17 for all blade elements. Once all blade elements are taken into account, the CAD file is ready for fabrication.

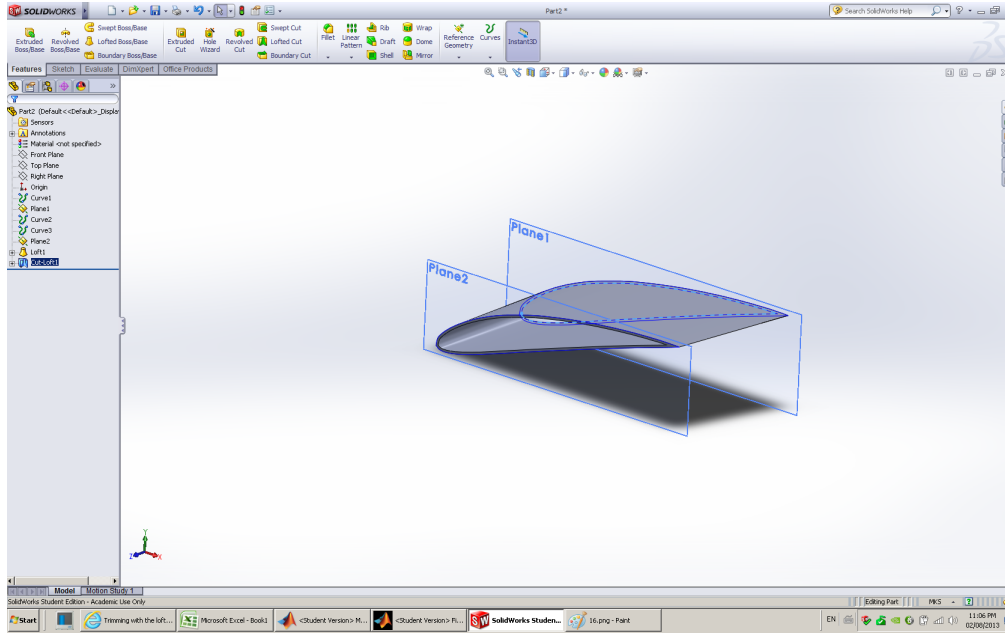


Figure 53: 1

## 9 Final Remarks

Although a reasonable effort was made to ensure the SWRDC code is as error-free and accurate as possible, the developer does not guarantee that SWRDC is bug-free, will not produce unrealistic or incorrect results, and will not crash. SWRDC has not been fully tested and you may use SWRDC for evaluation purposes only. Please interpret the results carefully and report back any confirmed errors to the developer. You may send your comments and questions to [mssessare@ucalgary.ca](mailto:mssessare@ucalgary.ca).

## References

- [1] Wood D. *Small Wind Turbines: Analysis, Design, and Application*. Green energy and technology, Springer, 2011.
- [2] Zhu WJ. Modelling of noise from wind turbines. Master's Thesis, Technical University of Denmark 2004.
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- [5] Drela M. XFOIL: An analysis and design system for low Reynolds number airfoils. *Conference on Low Reynolds Number Airfoil Aerodynamics*, University of Notre Dame, 1989.
- [6] Brooks TF, Pope DS, Marcolini MA, (US) PM. *Airfoil self-noise and prediction*. Washington, D.C. : National Aeronautics and Space Administration, Office of Management, Scientific and Technical Information Division, 1989.