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Development of a CAD design for locally manufactured small wind turbines with the use of CNC routers and 3D printers and monitoring the construction process for the creation of educational resources

Stage Assistant ingénieur 2ème année

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Glossary:

CNC : Computer Numerical Control

NTUA : National Technical University of Athens

ENSE^3 : Ecole National Supérieur de l'Eau, l'Energie et l'Environnement

RurERG : Rural Electrification Research Group

OSE : Open Source Ecology

ACE : Aire de Conception Energétique

GVCS : Global Village Construction Set

Acknowledgements

I am grateful to Kostas Latoufis to have supervise and advise me along my internship. By sharing his experience and knowledge on small manufactured wind turbine with me, he has made this project possible

I would like to express my sincere appreciation to the professor Nikos Hatziargyriou, to have welcome me and allow me at NTUA and to support the project presented here.

I would also like to thank Henda Djeridi for her interest in my internship and to have permit me to go further in those researches.

Abstract

English:

Small manufactured wind turbines build according to Hugh Piggott's guidance book are studied. The pros and cons about the use of **CNC machines** in this manufacturing process is observed. The use of industrial tools is expected to **reduce the time of construction** and the number of people needed to assemble a wind turbine. A 2.4m diameter turbine usually requires, after cautious preparations, roughly 6 days and around 10 peoples working 8 hours per day to get achieved within the association ACE. Does this time of construction can be reduced to 1 day? This eventually allow a production of wind turbine at an industrial level. This study would then be extended to blades 3D printing.

Three main changes have been studied in regards with the process described in "A wind turbine recipe book". Those changes allow different construction steps to be done quicker and by a machine instead of someone:

- The **blades** are usually carved with a chisel which makes it one of the longest step, it can easily lead to symmetry problems on the different blades. The best blade carved in NTUA has been scanned in 3D to be then **duplicated** on a **3D CNC milling machine**.

- Any piece required to build the wind turbine which has a suitable shape has been designed on Solidworks and FreeCAD and then printed on a **2D CNC laser-cut machine**. Those **flat pieces** are made of plywood and steel.

- The **coil winding method** has been adapted. The 9 copper coils of the turbine stator are winded using a drill on an axis, it would theoretically be possible to wind 3 coils at ounce. This is to replace the method described in the book, winding them one by one with a hand crank.

The **construction process** of the wind turbine has been **monitored**, aiming to create **educational resources**. To answer that need, a **CAD model** of the integral wind turbine has been designed on Solidworks, to demonstrate the running of the turbine, and the same model has been designed on FreeCAD, to obtain open source CAD parts of the turbine built.

French:

La fabrication de petites éoliennes telle qu'elle est décrite dans le guide de Hugh Piggott est étudié. Les avantages et inconvénients de l'utilisation de **fraiseuse CNC 3D** durant le procédé de fabrication sont considérés. Il est attendu que l'utilisation d'outils industriels puisse **réduire le temps de construction** et le nombre de personnes nécessaires pour créer et assembler une éolienne. Une turbine de diamètre 2.4m nécessite en principe, suite à des préparations attentives, six jours et 10 personnes travaillant 8h/jour en moyenne au sein de l'association ACE. Est-ce que le temps de construction peut être réduit à un jour ? Ceci permet la production de ce type d'éolienne à un niveau industriel. Cette étude peut être prolongée avec des projets d'impressions de pales à l'aide de 3D printers.

Trois changements principaux ont été étudiés en comparaison avec la version détaillée dans "A wind turbine recipe book". Ces changements permettent d'accélérer le temps de fabrication et de remplacer l'homme par une machine pour différentes étapes de construction de l'éolienne.

- Les **pales** sont habituellement sculptées à l'aide d'une plane ce qui requiert de la précision et du temps. Ce procédé peut facilement conduire à des imperfections et des problèmes de symétries entre les pales. La meilleure pale sculptée à NTUA a été scanné en 3D dans le but d'être **dupliquée** sur une **fraiseuse CNC 3D**.

- Chaque pièce requise pour construire l'éolienne ayant une forme convenable a été conçus sur Solidworks et FreeCAD puis, a été imprimée à l'aide d'une **machine CNC 2D par découpage laser**. Ces pièces sont constituées de **plaques de bois** contreplaqué et de **plaques de métal**.

- La **méthode d'enroulement des bobines** a été adaptée. Les 9 bobines de cuivre du stator de la turbine sont enroulées à l'aide d'une perceuse qui fait office de moteur sur un axe de rotation. Il est théoriquement possible d'enrouler 3 bobines à la fois. Ceci remplace la méthode décrite dans le livre, enrouler les bobines une à une à l'aide d'une manivelle.

Le **procédé de construction de l'éolienne** a été suivie dans le but de créer des **ressources éducatives**. Pour répondre à une telle demande, un **modèle CAD** de l'intégralité de la turbine a été conçus sur Solidworks, pour montrer le fonctionnement de la turbine, puis a été conçus sur FreeCAD, afin d'obtenir les pièces CAD de la turbine construite sur un format open-source.

I) Context

The book “**A wind turbine recipe book**”, written by the Scottish **Hugh Piggott** has inspired many people across the world to build, install and use **small manufactured wind turbine**. This book is a guide which lists and explains every step in the manufacturing process of small wind turbines. The book relates 6 different sizes of wind turbines, from 1.2m to 4.2m blades diameter.

Wind Empowerment is an international network of people that work on different fields related to wind power, it goes from technology, market assessment, education, maintenance or measurement.

At the INP university of **ENSE3**, the association **ACE** (Aire de conception énergétique), member of Wind Empowerment, focuses on the knowledge of this book for educational purpose, the 2nd and 3rd years member of the association teach to the 1st years how to build those wind turbines.

The lab **RurERG** “Rural Electrification Research Group”, member of Wind Empowerement network is a platform of researchers mainly working on off-grid renewable electrical supply. Tests on different off-grid renewable systems are performed on a small community of people in Rafina, next to Athens. A department of the lab focuses mainly on the manufacturing process of Hugh Piggott’s small wind turbines. **Kostas Latoufis**, Electrical and Electronic engineer, is working as a researcher in the Electric Power Division of NTUA, **National Technical University of Athens**. As a PhD student in the Fluids Division, he has been studying various aspects and approaches in the construction of small wind turbines.

Open Source Ecology (**OSE**) is a network of engineers, architects, farmers and supporters, whose main goal is the manufacturing of the **Global Village Construction Set** (**GVCS**). Their work allows the easy fabrication of the 50 different Industrial Machines required to build a small civilization with modern comforts. The American Marcin Jakubowski, founder of OSE, contacted RurERG to work on Research and Development on Hugh Piggott’s small manufactured wind turbines. This report explains and comments the outcomes of a first approach to this R&D project.

II) 3D Scan of the blades

A CNC milling machine can carve the curves and the integral shape of the turbine blades. As seen below, A milling machine is a rotating axis in steel that extracts material from a log of wood to create the shape desired. With its 3 rails, the head can move in a 3D space which allows to create complex shapes such as nonplanar surfaces.

Figure 1: CNC milling machine

The machine needs IGES files containing the CAD plans of the blade. This is one of the most common format in CAD. A scan of a hand-carved blade is performed to obtain the virtual design of the blade. The Iscan M300 fieldbus system from Immetric is used. The camera must be placed on various angle at 360 degrees around the blade placed on the table seen below:

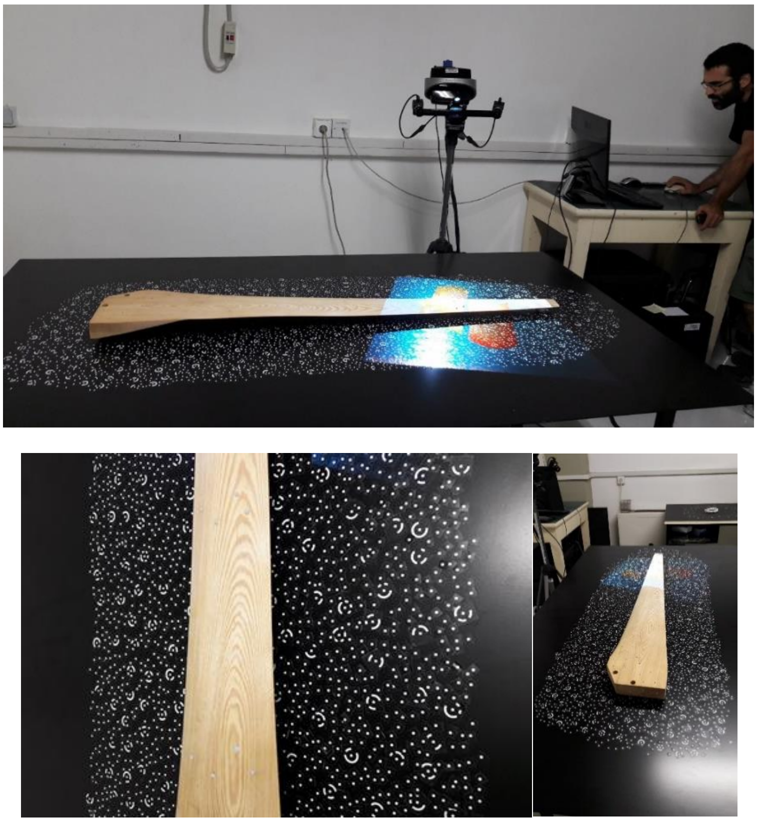


Figure 2: Scanning of the blade

The black table is covered of white stickers which are recognized by the camera as a referential in a 3D space. This system enables to calculate the coordinates of different points along the blade surface due to the light reflection on the object observed by the camera placed in different location. The carved blade is slightly longer than a meter, which is why the object had to be split in 3 different parts. In addition to that, both sides of the blade had to be considered separately. The 6 virtual surfaces created have been assembled together to form a solid corresponding to the blade initially scanned. As observed on the bottom left corner of the three pictures below, discontinuities and faulty faces had been fixed smoothed and up to be able to convert the IGES file into a Solidworks part.

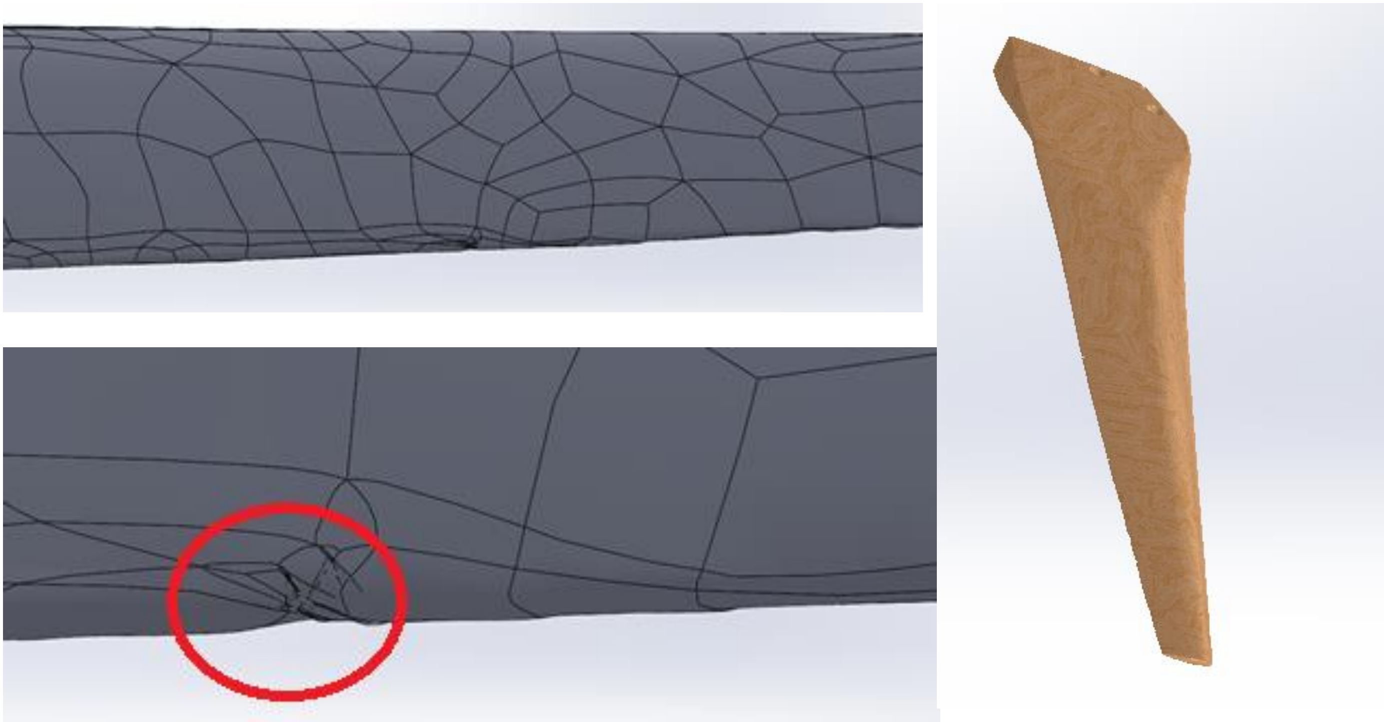


Figure 3: Solidworks Blade part

Two problems can generally occur when it comes to software conversions. The first one is directly linked to the face itself which can be faulty, for instance if it crosses another face. The second is a problem of discontinuity in between the different faces. Though, as observed in the picture below, a flaw, probably created by an impact or by a default during the carving process of the blade has been traduced in the software by a high number of crossing faces which couldn't be bconverted in Solidworks to represent a solid.

On the right-side picture above, the final blade part is observed with a wooden material assigned to it. The part will then be duplicate 3 times to be assembled with the rest of the turbine on Solidworks.

III) Solidworks CAD design of the wind turbine

Following step by step the different chapters of the book, every piece needed to build the turbine is created and they are assembled in 9 different sub-assembly folders on Solidworks. In order, the blades assembly, the rotors, the coil winder, the stator, the hub trailer, the steel body, the tail and the tower & foundation of the turbine will be studied independently. Then, the final assembly will be considered. Every piece has been designed according to the book dimensions of a 2.4m diameter wind turbine.

III)a) Parts and sub-assembly design

The entire turbine is made of about 70 pieces of steel and plywood which doesn't includes the one required to mold the rotors and stator, neither the screws, bolts and nuts which are required to assemble it. All those parts have been numbered, pictured and listed in the Appendices. Dimensions and shapes of some pieces have been recorded.

- **A) Blades:**

An optimal number of screw has been considered according to the blade dimensions. However, most of the turbines don't have the same dimension exactly. The file has been done so the positions of the holes can adapt in function of few values which indicate the dimension of the blades used. See scheme below:

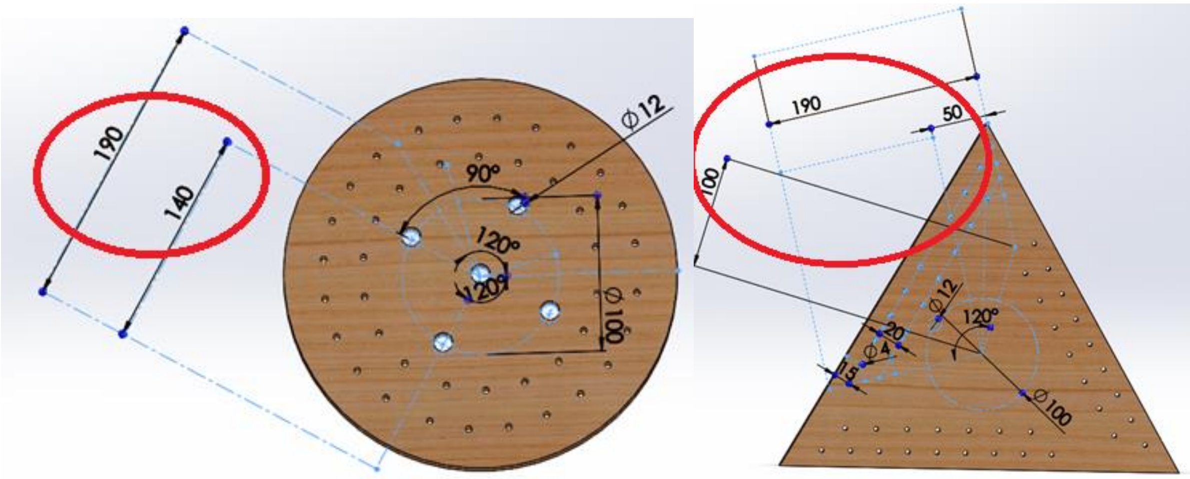


Figure 4: Blade supports, screws repartition

A total of 90 screws are used to assemble the blades together. The book gave dimensions to respect: each screw must be at least 25mm far from another one, two lines of screw must be designed on both supports. Kostas's experience helped to optimize the dimension requirements: the lines of screws should be sufficiently far away from each other but no screw should be closer than 15mm from the edge of a blade. When the two supports are facing each other, the design needs to ensure that no screw path crosses another one. This can be checked below:

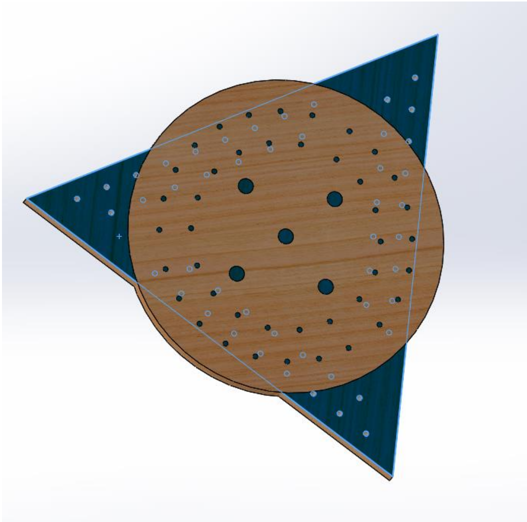


Figure 5: Screws check of the blades supports

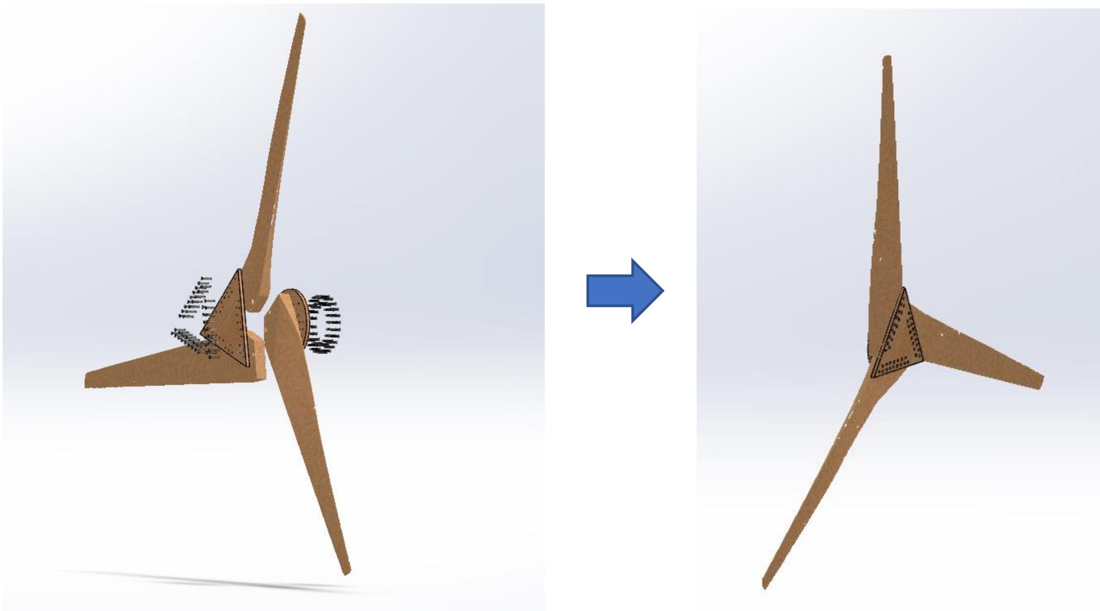


Figure 6: Blades sub-assembly

This sub-assembly of the blades has been designed to resist to strong stresses coming from the spinning of the assembly. The screws are spread out as much as possible to limit concentration of constraints.

- **B) Coil winder:**

Winding the stator coils is one of the first step that follows the carving of the blades. The process is very simple, a copper wire is wind around an axis by spinning a wooden frame. The shape of the wooden frame is designed to shape the coil (seen up-right).

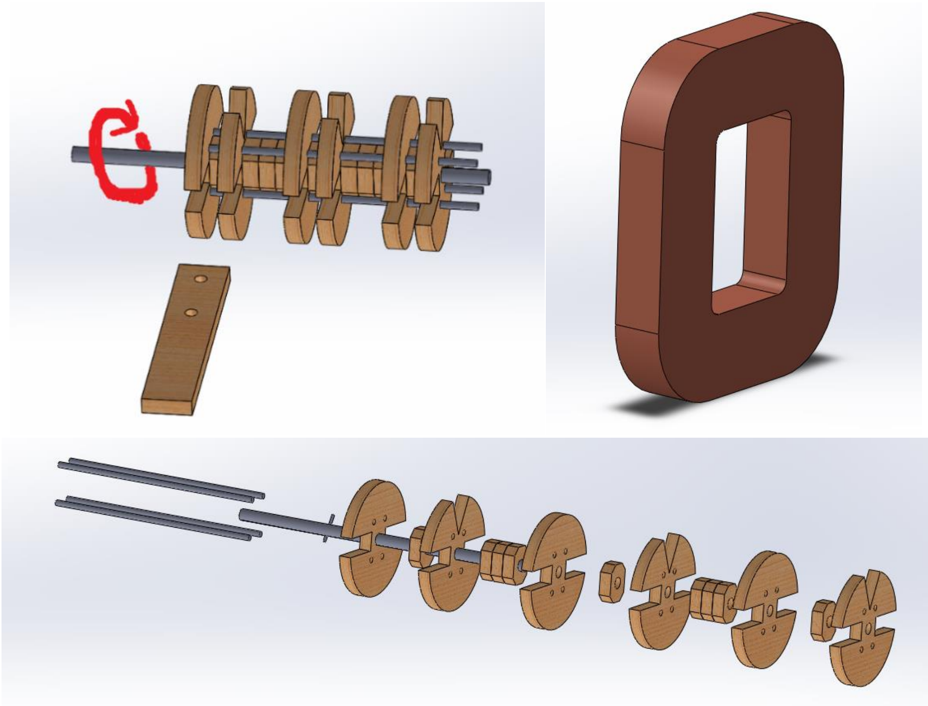
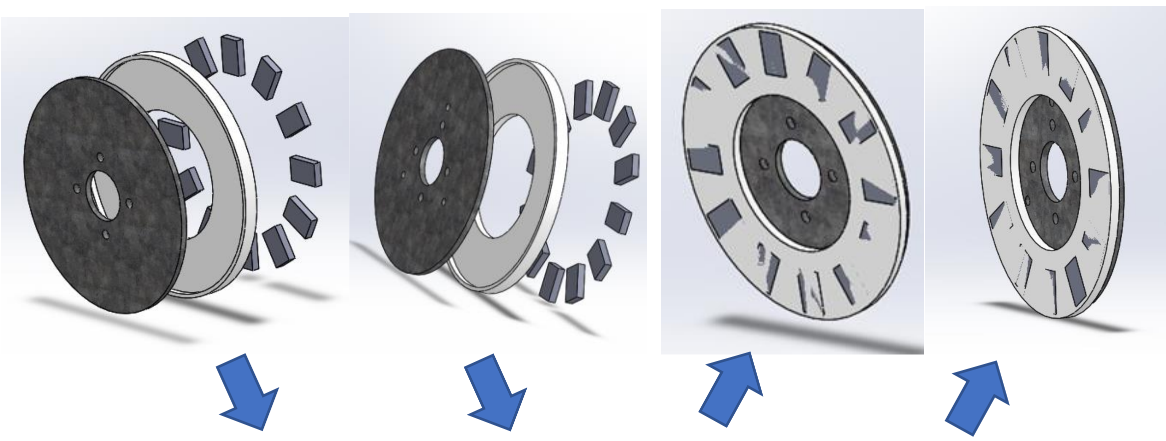


Figure 7: Coil winder sub-assembly

The innovation tried here is to use a drill to spin the axis and to wind 3 coils at a time instead of one. Indeed, the stator contains 9 different coils in total. It is in fact 3 groups made of three coils each, placed in series. This configuration permits to obtain a three-phased signal at the output. Three wooden frames have been placed next to each other on the drill axis. If the three coils can be made from the same wire, it would even slightly improve the efficiency of the stator by reducing the number of junctions between the coils. Therefore, it reduces the electricity losses, and is a gain of time because the wires must be joined one time instead of 7. Each wooden frame is made of three different pieces, the middle piece is the most important as it gives to the coil its square shape and its right thickness. The two side pieces of wood are used to block the wire and count the number of tours. The overall is maintained by a central thread and four peripherical threads with a smaller diameter.

- **C) Rotors:**

As its name indicates, the rotor is the part of the turbine that rotates according to the blades. Two rotors must be designed, they're placed on each side of the stator. They each have the same number of magnets as the number of coils in the stator (12).



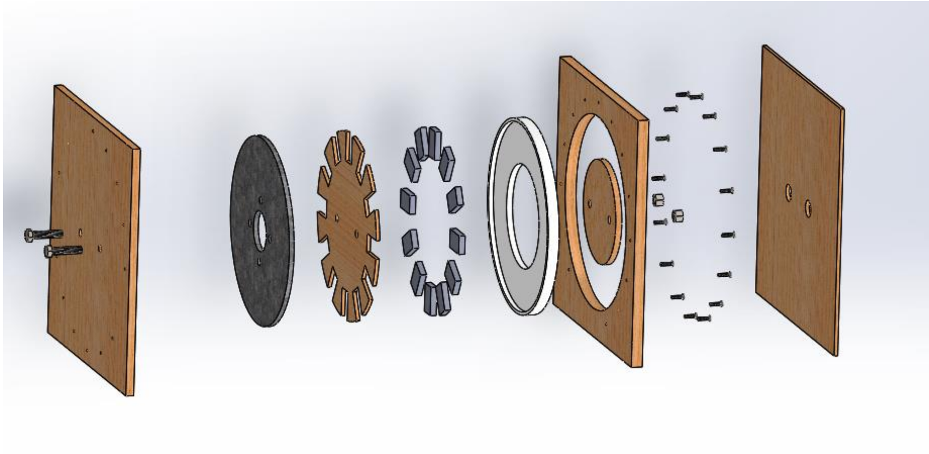


Figure 8: Rotors sub-assembly

As seen above, to design the rotors, a plywood mold must be used. It allows the resin (white disk here) to dry and to block the magnets together on a galvanized steel disk. For more convenience and for a matter of time, two plywood molds have been printed to design both rotors in the same time.

- **D) Stator:**

Very much like the rotors, the stator is made with a wooden mold which allows the resin to dry and trap the 12 coils together. The stator, which doesn't move while the blades are spinning, is placed on the turbine with three threads.

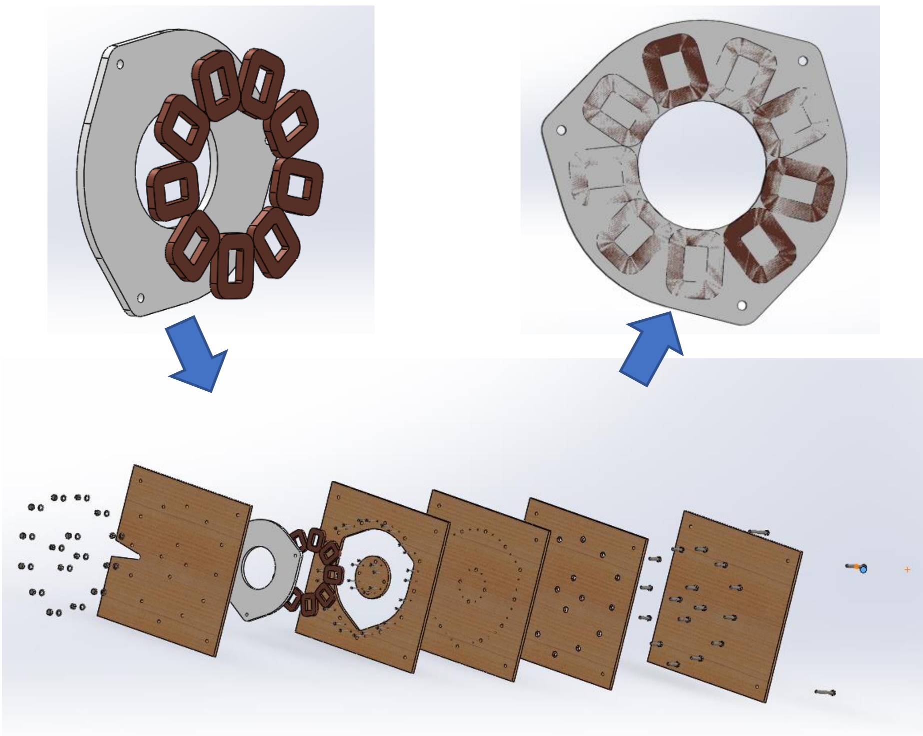


Figure 9: Stator sub-assembly

The electricity is generated in the copper coils from the electromagnetic field created by the rotating magnets. This energy is collected and goes out through cables on one side of the stator, To let the cables out of the mold while it is closed, a part of the plywood with the shape of a V has been removed on the top cover of the mold.

- **E) Hub trailer:**

The hub trailer allows blades and rotors to spin around an axis. This piece is obtained already mounted from cars or car trailers. The Solidworks design has only been realized for educational purposes.

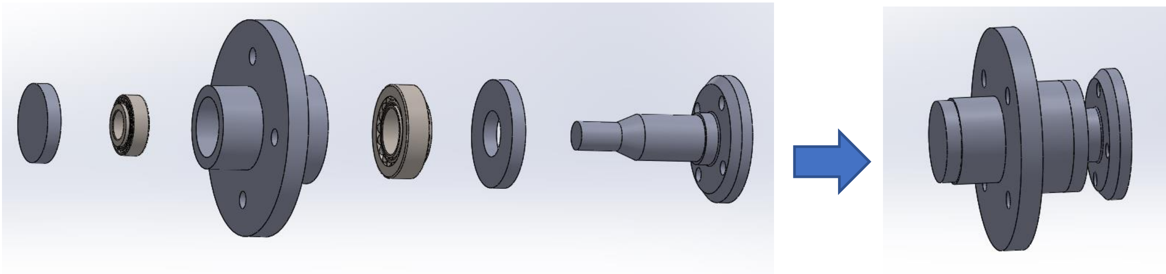


Figure 10: Hub trailer sub-assembly

As seen above, the hub trailer is made of one axis which is placed on the body of the turbine, called the "stub axed shaft". The other part, the "hub flange" is able to rotate. It connects the blades and rotors to the rest of the structure. Two tapered roller bearings are used to maintain the hub flange and the shaft together.

- **F) Steel body:**

The body of the turbine is made exclusively of steel, it allows to connect the tail, the hub trailer and the tower of the turbine. Several flat pieces are designed to introduce various angles in the body of the turbine so their dimension must be checked very carefully.

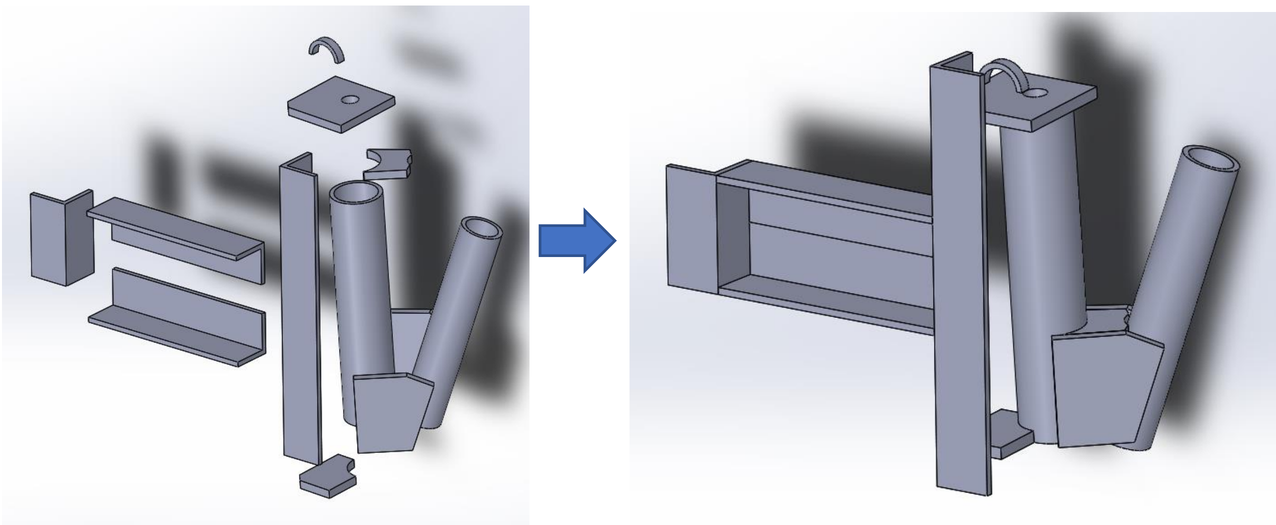


Figure 11: Steel body sub-assembly

The diagonal pole on the right of the body is used to place the tail and acts like a hinge. The wires coming out of the stator are dragged down the tower pipe by the arc placed on the top.

- **G) Tail:**

Some changes have been applied to design the tail compared with the book's version. Flat pieces such as the triangular reinforcement seen below have been invented to enhance the time of construction of the tail. Indeed, because some pieces are designed on a CNC machine, the assembly and the welding of this sub-assembly is now much more quicker and simple as the different pieces fit together like a puzzle which simplifies the welding.

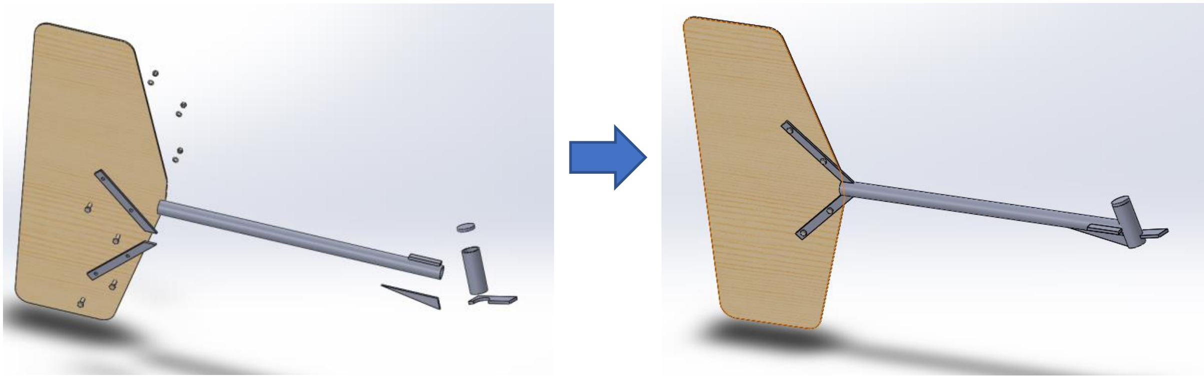


Figure 12: Tail sub-assembly

The angles introduced must allow the tail to be vertically orientated in its standard position.

H) Tower and foundation:

Towers and foundations of the wind turbine are studied together as they both aren't built in the final model. They have been created on Solidworks to help to realize an educational guide on how to place and build up foundations and the tower of the wind turbine. This guide which relates the dimensions and the positions of the different pieces is available in NTUA.

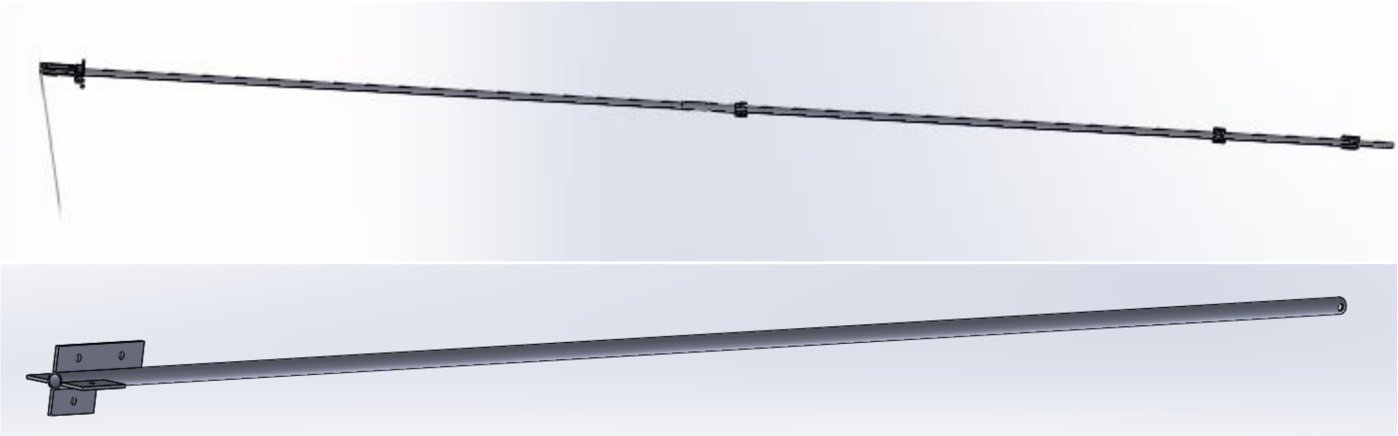


Figure 13: Tower and gin pole assembly

The 12 meters long turbine tower is observed above with the 6 meters gin pole below it. The tower is made of two six meters long poles assembled together, so, the same kind of pole can be used for the gin pole. The gin pole acts like a crane in the hoisting process of the tower.

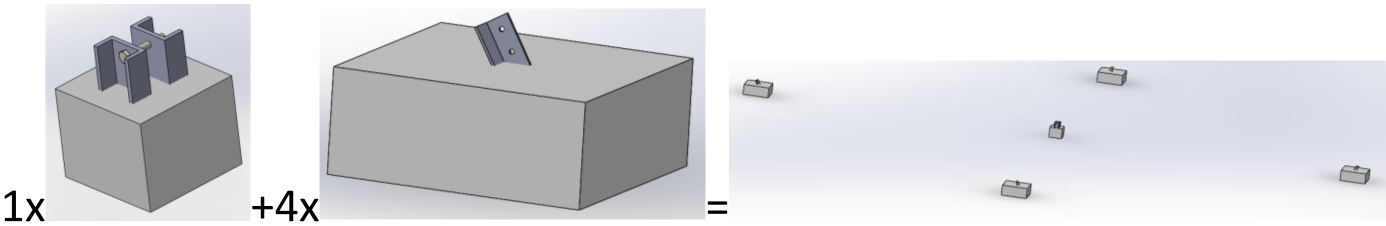


Figure 14: Foundations of the turbine

As seen above, the foundations of the turbine are made of five blocks of concrete. The central block supports the gin pole and the tower of the turbine. The 4 others are used to attach cables to maintain the tower standing. One of those four blocks is used as an hoisting block from which the gin pole can be pulled down which brings the turbine up.

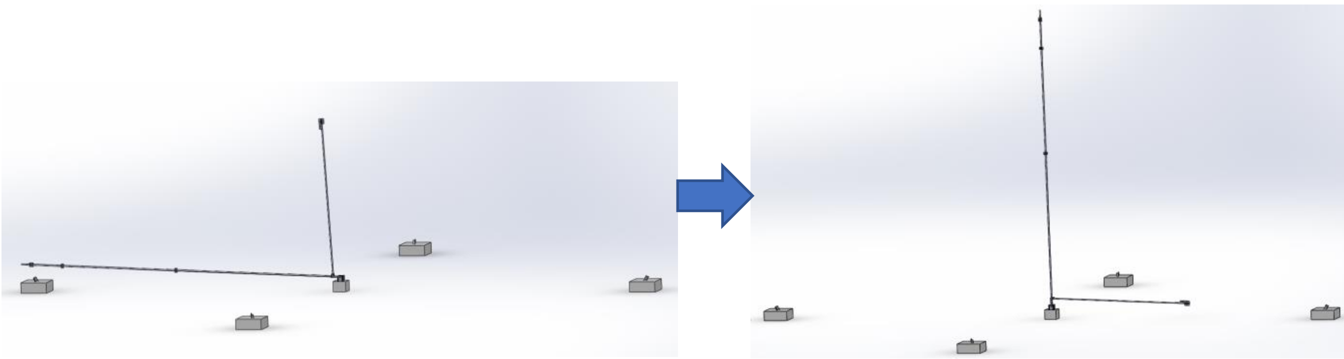


Figure 15: Foundations, tower and gin pole sub-assembly

The three entities are observed together. On the left side, they're observed in the position turbine down and on the right side, in the position turbine up.

III)b) Final assembly

The final assembly on Solidworks has been performed after several checks. The first one is to make sure that once rotors and stator are placed on their axis, the coils on magnets are placed at the exact same distance from this axis.

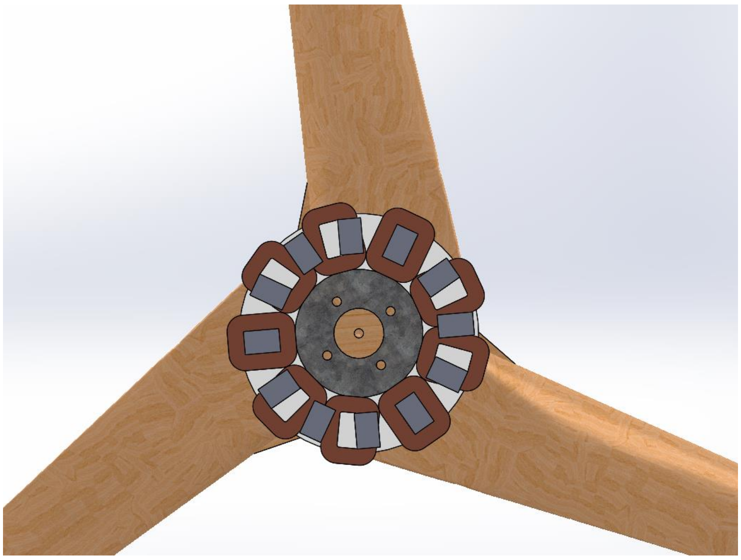


Figure 16: Distance check between magnets and coils

Magnets and rotors are placed in a convenient way above. As observed, the squared gaps of the coils correspond to the size of the magnets. The aim is to place the magnets in a way that they match exactly to those holes when watched from along the rotating axis.

Then it is checked that the tail ends up parallel to the tower in its standard position as suggested earlier.

Finally, the two extreme angles in between the tails and the blades of the turbine are checked

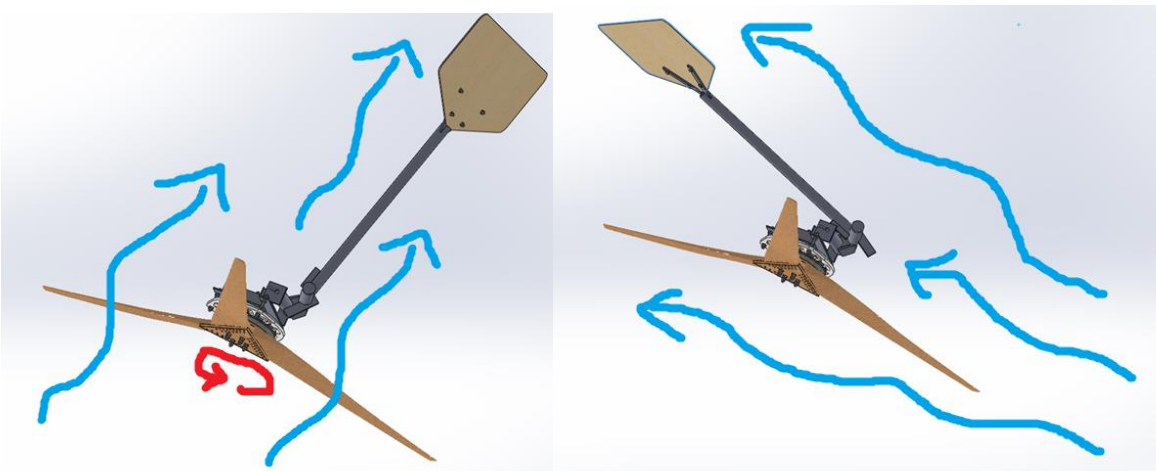


Figure 17: Tail extreme positions of the turbine

On the left picture of the figure above, the turbine is seen in its standard position, the wind blows normal to the blades surface and along the tail which allows the turbine to rotate. In the second position, on the right picture, the mechanical brake of the turbine is observed: above the cut-out speed (wind at roughly 12m/s), the tail furls and the wind starts flowing along blades and the tail which disables the turbine rotation. This method prevents any damages on the turbine in case of strong gusts.

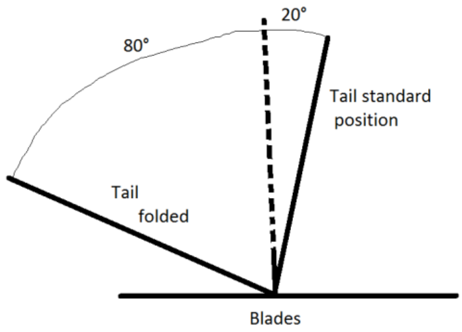


Figure 18: Tail movement scheme

The scheme above, which represents a top view of the turbine, indicates the angles that the brakes must respect. Two brakes are placed on the tail sub-assembly, they constrain the tail movement and allow it to respect those angles.

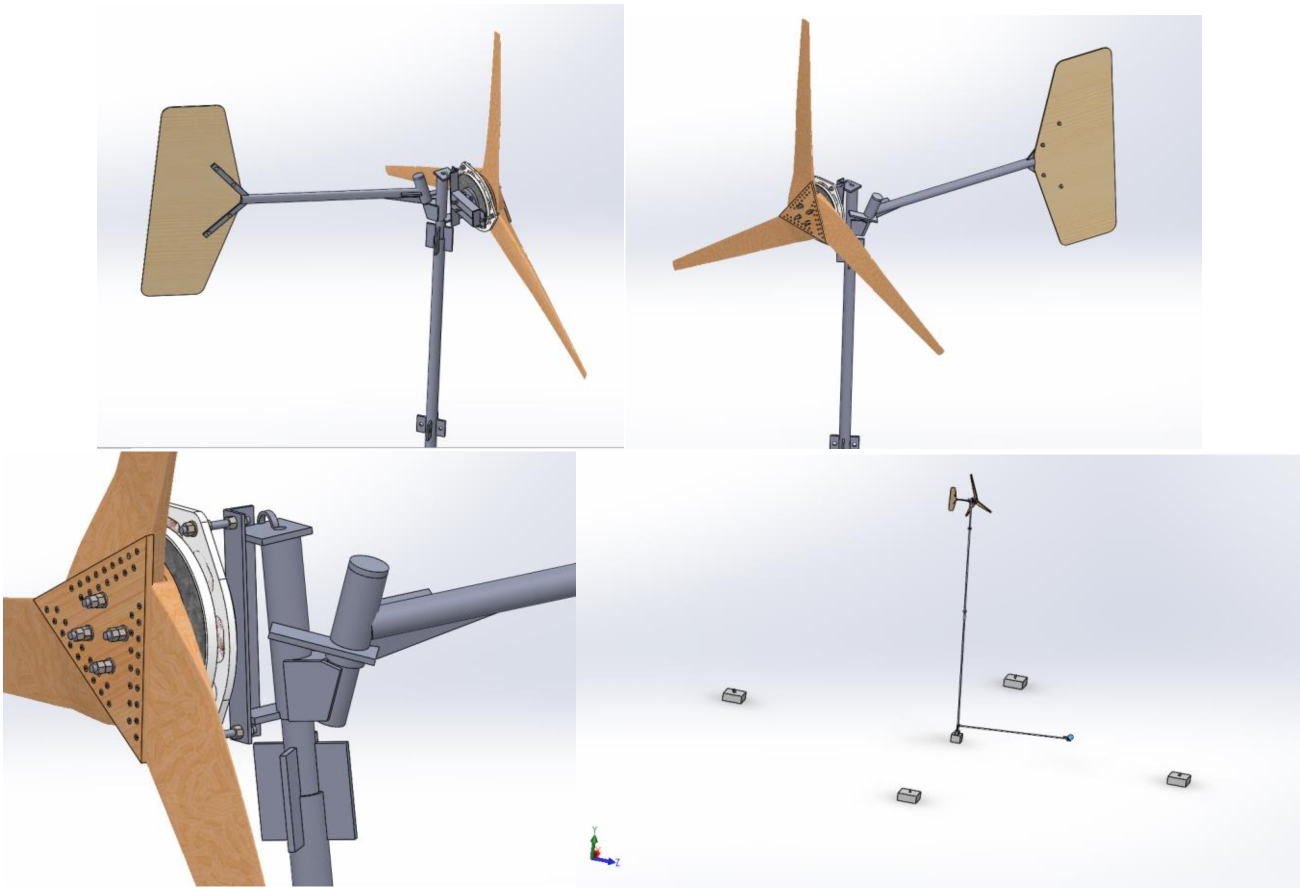


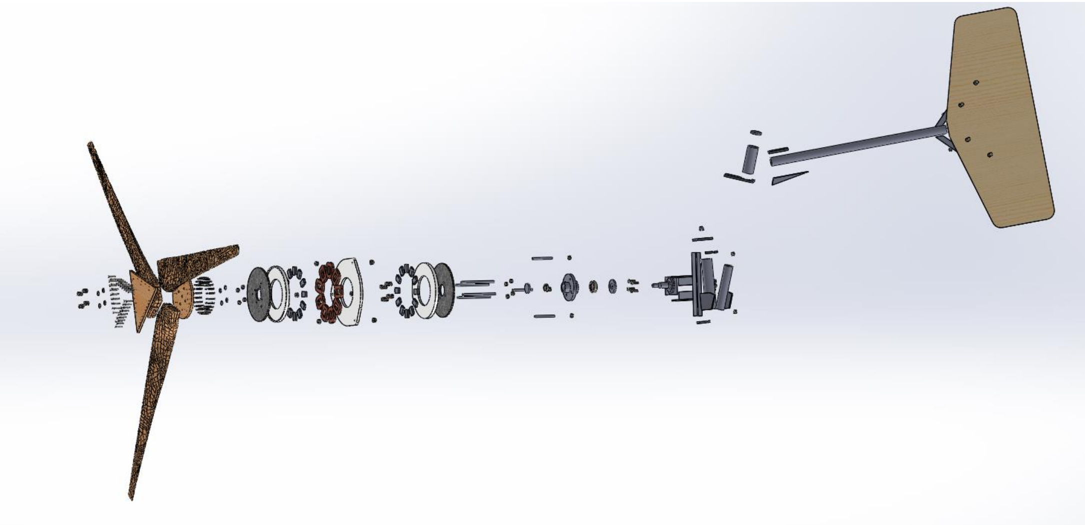
Figure 19: Final turbine Solidworks assembly

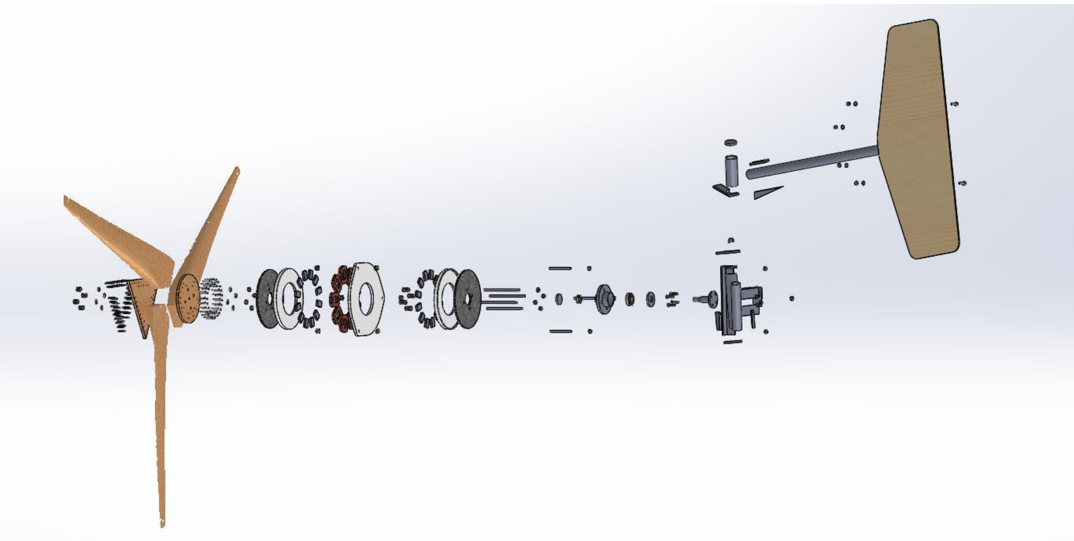
The pictures above are representing the final assembly of the turbine. The turbine itself is seen firstly from the front and then from the back. Then a detail of the turbine's body is observed. Finally, the overall turbine with tower and foundations is seen. The Solidworks file permit to leave free the movements of the turbine as it should theoretically be. Therefore, on this file, the pieces that have free movements can be moved and observed simply by rotating the blades. Also, the tower standing up can be observed by moving the gin pole and showing the hoisting movement of the turbine.

This model can be used for educational purposes to get a better understanding of Hugh Piggott's small manufactured wind turbines and for dimensions checking to help to build a 2.4m diameter turbine.

III)d) Exploded view

Here, exploded views of the entire turbine has been realized. This view has been realized only for educational purposes. Every piece that is part of the wind turbine is here observed with details.





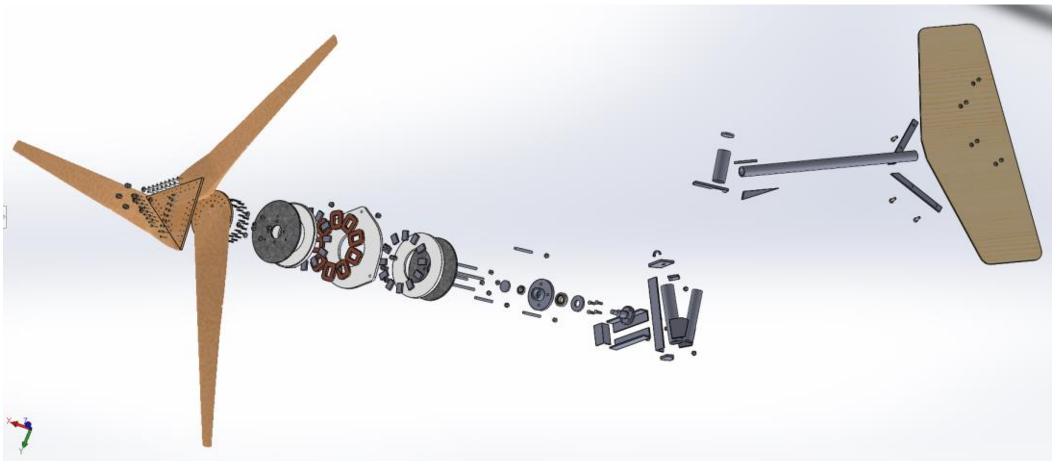


Figure 20: Exploded views of the 2.4m diameter wind turbine

The aim was to provide a detailed image of what is inside a wind turbine, the different pieces displayed on the axis are grouped together. For instance, the steel disk, the magnets and the resin which constitutes all together a rotor are placed not too far from each other. The view becomes then more readable for someone that doesn't know the different entities of a wind turbine.

IV) Flat pieces for CNC machine

Every flat piece constituting the turbine is printed through a CNC laser-cut machine, either if it is made of steel or plywood.

Figure 21: CNC laser-cut machine

The machine presented above has been used. The picture shows the mechanical arm, in the red circle. It is equipped with a laser that cuts steel and plywood with a sufficient level of accuracy. This arm moves in a 2D plan parallel to the surface of the material sheet. The laser cuts through the layer and design the shape entered in the laptop on the left side of the picture. A list of every flat piece useful for the turbine is shown below. They have been grouped by material and by thickness to observe what part can come from the same piece of material.

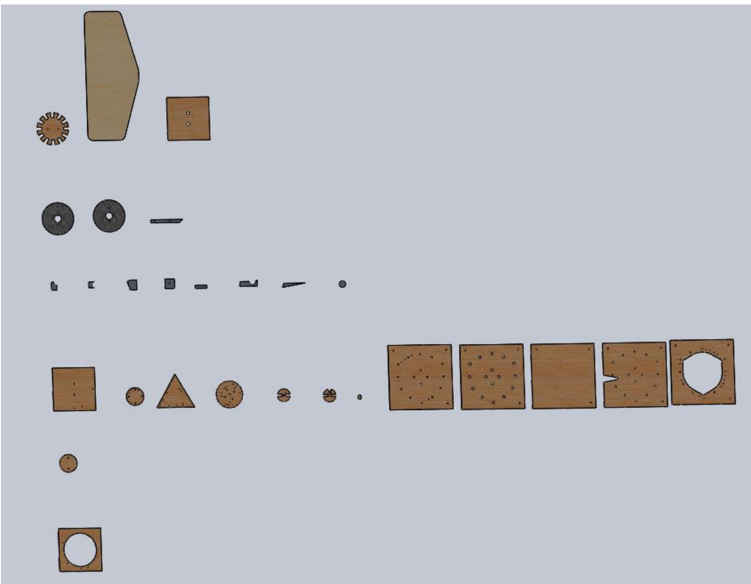


Figure 22; Flat pieces on Solidworks

Those pieces are converted in a DXF file. The DXF file, observed below, represents every flat piece to be designed. On the file, their material (plywood or steel), their thickness and the quantity needed is specified next to the piece shape.

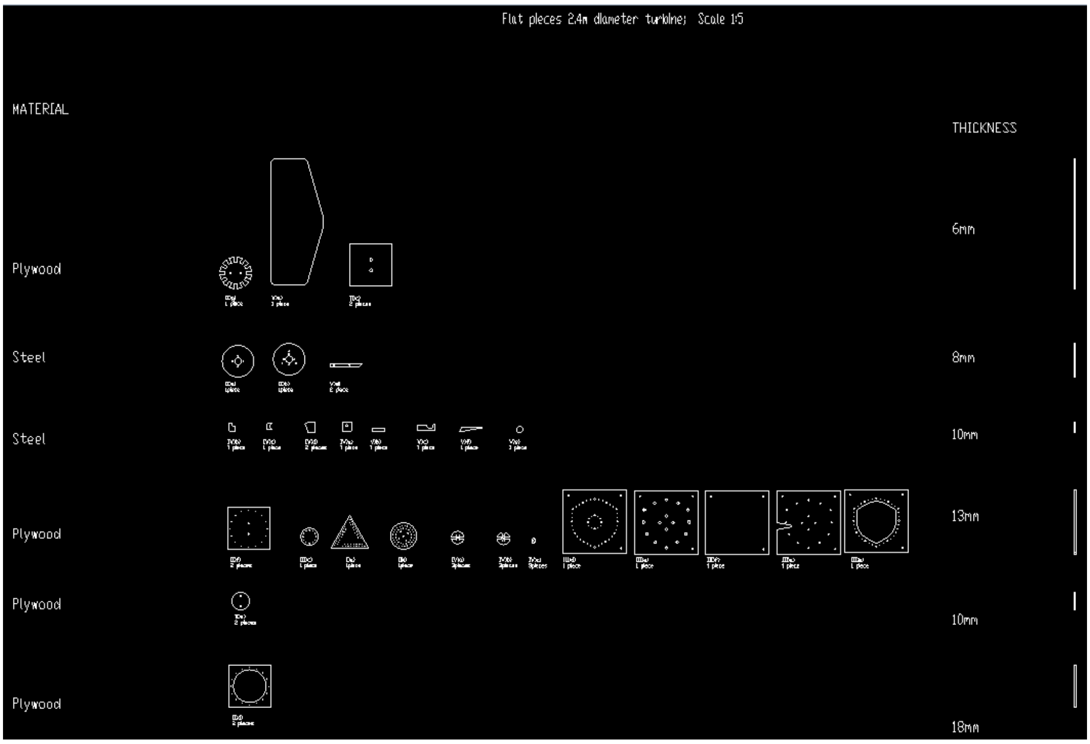


Figure 23: Total flat pieces for CNC machine

The pieces that can come from the same piece of material are joined together in a single file and their positions are optimized to take the less space possible.

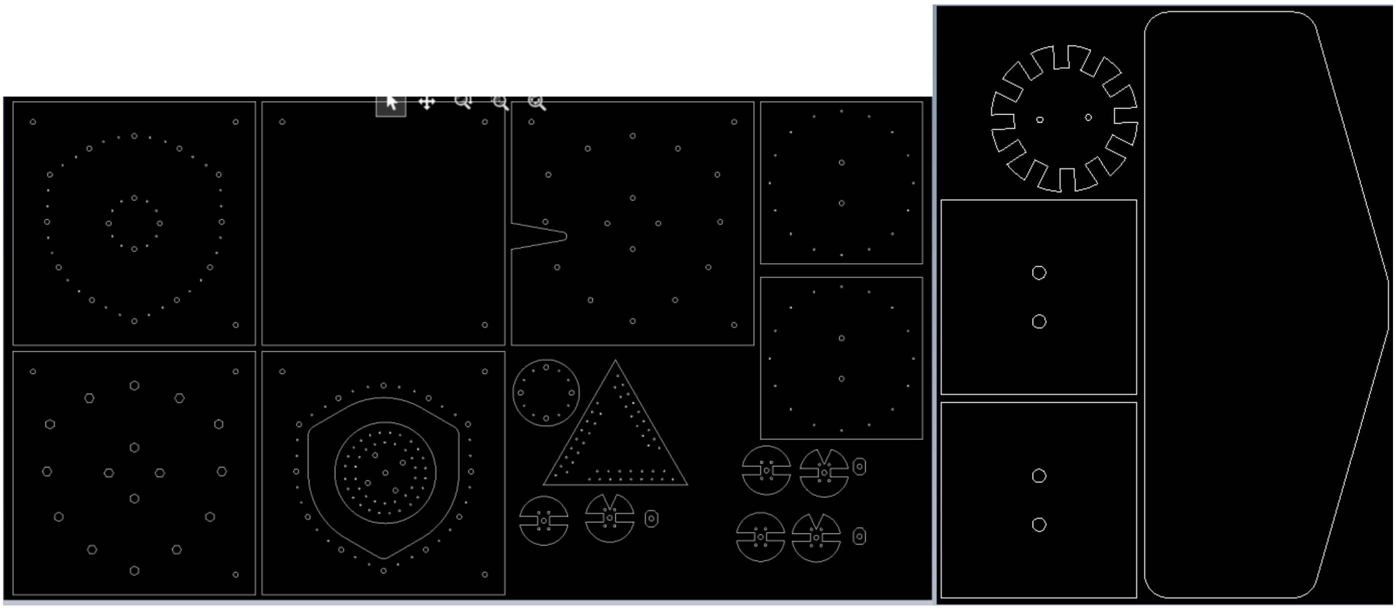


Figure 24: Group of pieces with same thickness and material

Here the pieces of plywood 12mm are observed on the right and the plywood 6mm are observed on the left. It is noticed that for those flat pieces, the 2D CNC machine is an ideal solution as it doesn't need to shape parts in 3D but only needs to cut the parts in a two dimensions plan. Therefore, the cost to print those pieces is around 300 euros which is much cheaper than to carve the blades.

V) Steps of construction

The construction of the turbine is realized, the aim is to check the CAD design and find other improvements to this method. Also, the time of the steps of construction is recorded to give an idea of the time saved compared with the original method from the book. To start, every piece required are gathered up.

Figure 25: Pieces required for the 2.4m turbine

On the right side of the picture, the different parts of the rotor molds are shown. Down on the right, there is products for the resin casting and the magnets. In the middle there is the 5 layers of the stator mold. On their left, are every bolts, screws, washers and nuts required for the turbine. On the middle left are placed the hub trailer, threads, pipes, angles and flat pieces made of steel. The copper wire and CNC pieces needed to wind the coils are presented in between the steel and the stator mold. Above, the tail is observed. In the bottom left corner there is the triangle and circle required for the blade assembly.

The construction from here to the final turbine assembly will be presented and commented step by step. A summary of the time and number of persons saved is presented next section.

V)a) Mold assembly

One of the first step is to assemble the three molds together, a lot of time is saved as the pieces are already printed out from the CNC machine. The assembly observed below is realized in a very short time as it consists now only in placing and screwing the different parts together.

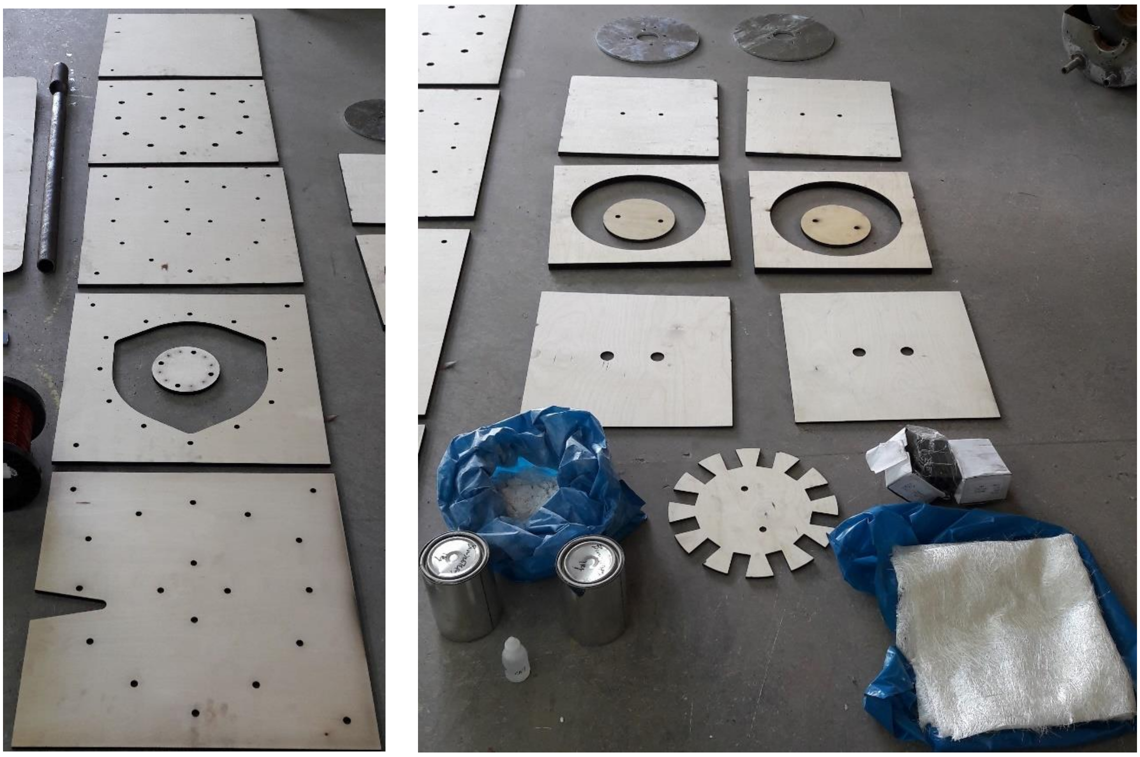


Figure 26: Parts of the Stator and rotors molds

It is also observed that the CNC machine designs very clean pieces compared to human made mold parts. This can be crucial when it comes to the extraction of the resin from the molds. Indeed, flaws in the mold can lead to problems or impossibility to take the part out of the mold.

Figure 27: Rotors and stator molds assembled

V)b) Coil winder

The assembly of the coil winder is observed below. It is mounted a first time and tried to see if the method works. Then, in a second time it is mounted again and all the coils are winded, the total time to wind the 9 coils required is recorded for this method.

Figure 28: Coil winder assembly

It is seen above that the coil winder created is made of three coil frames placed in series on an axis. A drill powers the axis rotation. Finally, a counter placed along a coil frame displays the number of tours already performed. For such a turbine, each coil has 90 loops which makes the winding process very long.

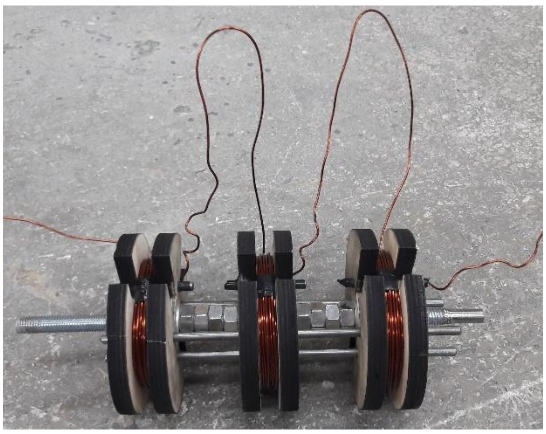


Figure 29: Coils winded

Here, the coils are winded at a greater speed and three of them are winded one by one which permits to obtain them already connected. On average, it has been recorded that 5 min is required to mount the coil winder on the axis, 2 min is required to place it correctly on the drill, and 8 min is required to wind the three afterwards, finally, 8 minutes are required to tape them and extract them from the coil winder. This represents a huge time saving compared to the hand crank method which takes more than twice the amount of time found here. Besides, once printed, the coil winder can be reused for other turbines.

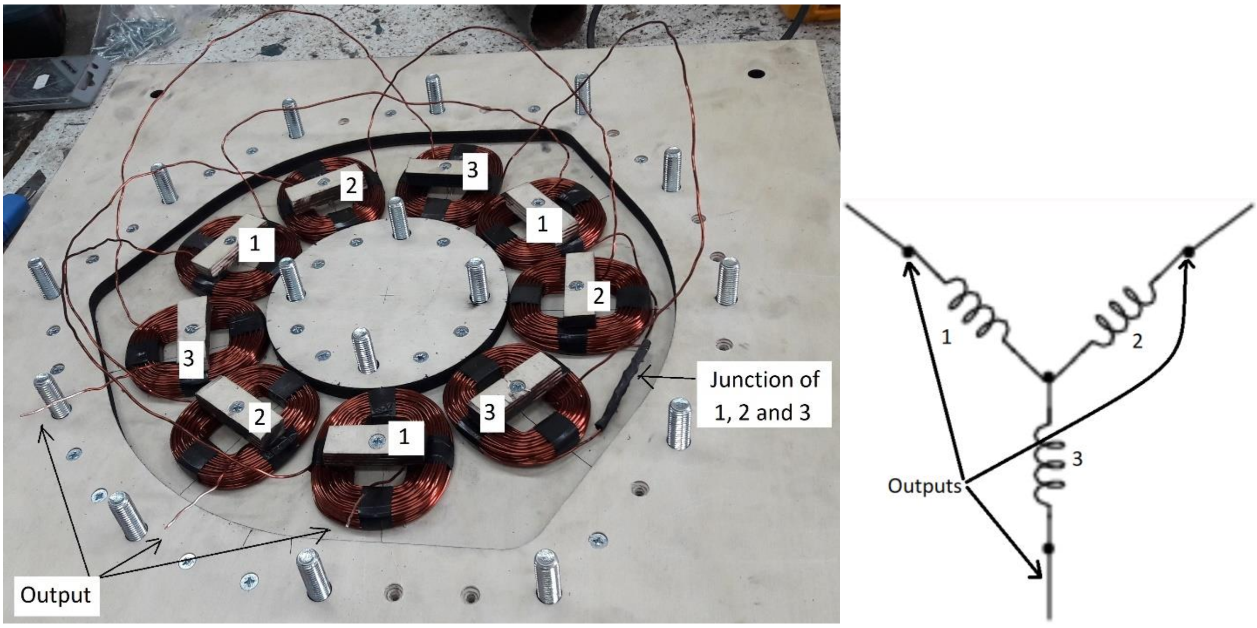


Figure 30: Coils placement in the stator mold

The final stage consists of joining the 9 coils together according to the stator shape. The electrical scheme on the right side above, shows the connection of a three-phased currant, the equivalent is observed on the left side with the coils winded. One of the greatest advantage of this method compared to the original is that here, only one connection in between the coils is done. It has been deduced that a length of 30cm of copper wire must be left in between two coils in series to be placed properly.

V)c) Stator and rotors molding

Once molds, magnets and coils are ready. A vinyl ester resin is made mixing talc, liquid vinyl ester and a catalyzer that turns the dough into solid resin.

Figure 31: Stator and rotor mold filling

The molds are generously filled up with resin using fiberglass which protects the resin faces of the stator and rotors.

Figure 32: Drying the molds

The molds are then closed tight. Bolts and nuts are used for the stator. Steel pieces and the electromagnetic field of the magnets are used for the rotors. After 3 hours on average, the molds are opened and the stator and rotors are extracted. The stator is then drilled in three locations, threads will hold the stator in between the two rotors in the final assembly.

Figure 33: Rotors and stator extracted from their molds

The three parts out of the molds are observed.

V)d) Steel welding

The welding of the steel pieces is one of the longest and the hardest task. Two sub-assemblies need welding. The body of the turbine and the tail observed below before they are welded.

Figure 34: Steel pieces to weld

Those pieces are welded as presented on the picture below.

Figure 35: Bar metal arc welding

A bar metal arc welding method is used here, this method requires accuracy and concentration. Other method such as the gas tungsten arc welding might permit to obtain a better result in a shorter amount of time, on the other hand, this method is more expensive.

Figure 36: Steps of welding of the body frame of the turbine

As seen in the 6 pictures above, in the first place, the angles are assembled together to create the frame of the wind turbine.

The hub trailer ensures the connection of the rotors and the blades to the rest of the turbine while it allows their rotation. This piece is obtained from a trailer as shown in the middle-up picture.

The steel frame is then drilled to fit the shaft of the hub. The welding between shaft and steel frame is observed on the bottom left picture. Afterwards, the yaw pipe, that goes on the top of the tower and sustains the turbine is welded to the frame.

Then, the entire piece is placed with a 55° angle as described in the book, the inner pipe of the tail hinge of the turbine is welded vertically above it. As seen on the last picture on the bottom right corner of the figure above, the junction reinforcements that go between the yaw pipe and the tail hinge have been designed on CAD to fit perfectly and to help to find the location of the other pieces. This allows to not lose time during the welding instead of measuring angles and distances to calculate the next piece location. Everything can get assembled quickly and finally the entire wind turbine frame is welded.

Another part that requires a lot of welding is the tail.

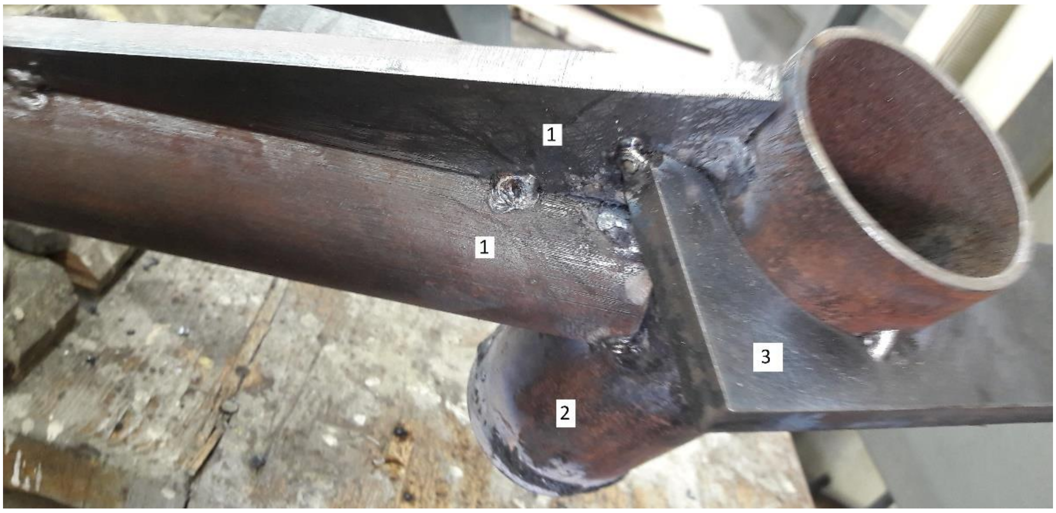


Figure 37: Tail welding process details

As seen here, welding the tail is faster with CNC pieces. Indeed, the triangle called 1 above directly gives the placement of the two pipes, tail boom and outer hinge of the tail. In the original method, it is asked to weld the two pipes together according an angle of 110° and it takes easily a while to measure. Here, the triangle is directly welded at the end of the tail boom, 1, and the second pipe directly goes along the triangle with the correct angle, 2.

Using the same concept, one of the brakes, of the tail can be welded touching the triangular piece which simplifies the operation and reduces the risk of placing it wrong, 3.

The tail is finally placed on the top of the turbine frame. This step is required to weld vertically the brackets of the tail on the tail boom.

Figure 38: Tail brackets welding

The entire welding process takes a long amount of time but a professional welder can certainly realize the same task faster and with a better result than someone learning welding for the first time. Therefore, the time estimation of the welding process is hard to determine and is proper to each welder. In any case, when comparing the same person performing the welding with the two different method, it appears clearly that the steel pieces designed with a CNC machine allow to be faster.

V)e) Blades assembly

Unfortunately, for a matter of money, the 3D scanned blades haven't been ordered. Nevertheless, the amount of money and the time to print them out have been recorded. One blade would cost 550 euros.

It has been taken in account that to print them requires first to print out a negative of the blade which is then used to support the blade while the opposite surface is carved. As printing several blades require only one negative, the price is more affordable if many blades are designed (industrial scale) but it makes it too expensive for a single turbine.

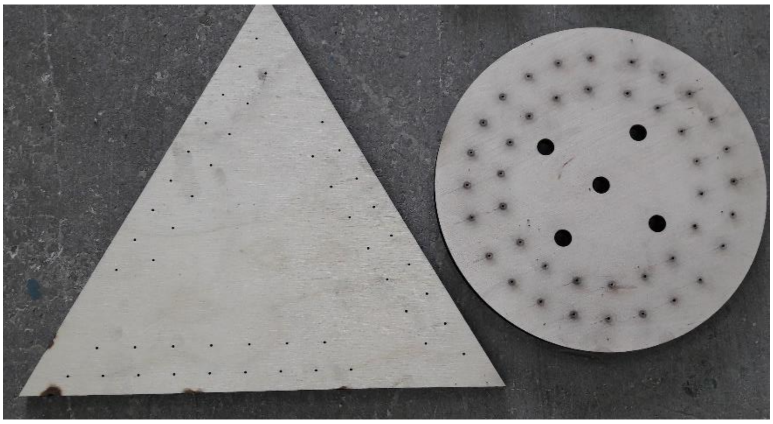


Figure 39: Triangle and circle blades supports

The triangle and circle required to support the blades together have been printed out from the 2D CNC machine, it has been checked up that the shapes are correct and that no screws are crossing each other while they are getting assembled. Anyway, the time to assemble the blades would be the same as in the original method. Beside the fact there is no time saving here, the optimized design of the triangle and circle ensure a strong assembly in between the blades. Once again, the use of the CNC machine over human prevents flaws that would compromise the turbine installation. If those two pieces aren't designed correctly, a significant amount of time could be lost trying to place correctly the blades.

V)f) Final assembly

At this stage, the different sub-assemblies of the turbine must be assembled together.

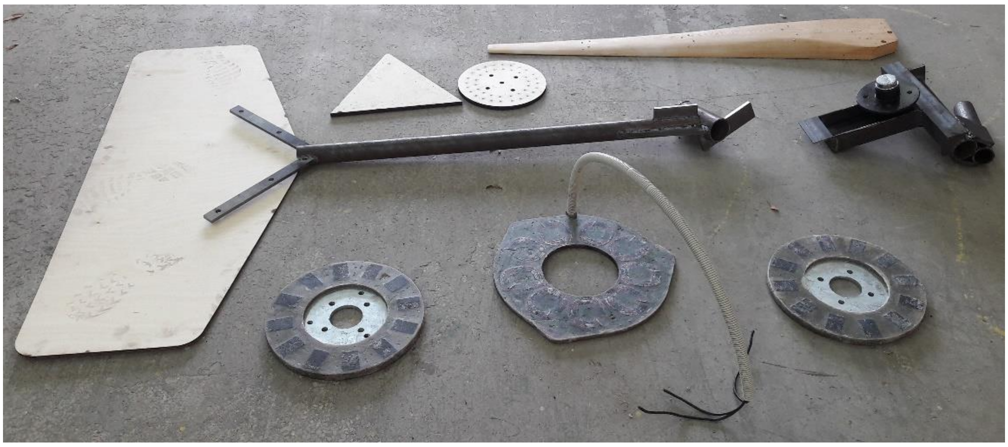


Figure 40: Sub-assemblies of the turbine

The three components of the blades assembly are observed above, in the middle, the tail and the steel body of the turbine, below, the two rotors and the stator are seen.

The next step is to place and assemble one after the other, the rotors and stators on the body of the turbine.

Figure 41: Generator assembly

It is shown here that one rotor is screwed first on the hub trailer, then the stator is fixed up to the frame of the turbine body and the last rotor is added up on the top. Finally, the spacing in between rotors and stator is optimized and the nuts that hold them are tighten up. The final result is shown below.

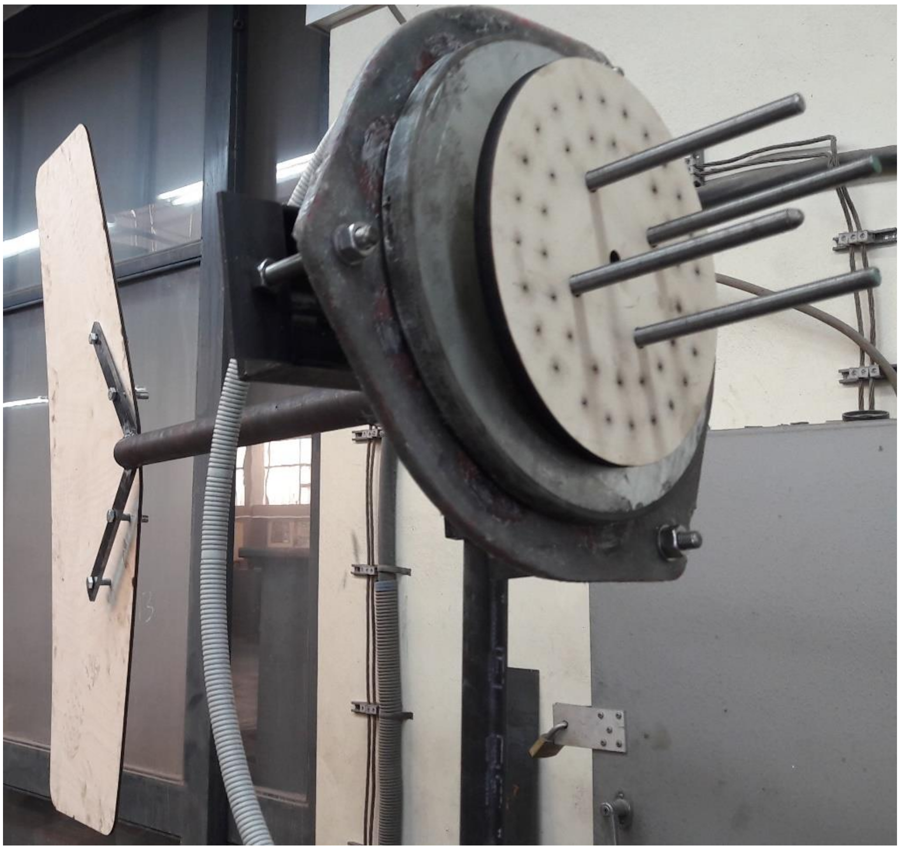


Figure 42: Final turbine

It has been proven here that the turbine can be built in a faster way using flat pieces designed on a CNC machine, 3D scanned blades and a different way to wind the coils. A summary of the time and number of persons saved is presented next.

VI) Methods comparison

Steps of construction	Time		Minimum number of persons required	
	Original method	New method	Original method	New method
Design of the flat pieces	6h	2h	3	1
Blades carving	5h	2h	3	1
Assembly of the moulds	1h30min	35min	2	2
Preparing galvanized disks	30min	30min	1	1
Magnets placing	30min	28min	2	2
Preparing the hub	25min	25min	1	1
Metal work (not welding)	2h	41min	2	2
Coils winding	3h	1h10min	2	2
Placing and connecting coils in the stator mold	2h	1h 08min	1	1
Rotors casting	1h30min	1h30min	2	2
Stator casting	41min	41min	2	2
Extracting rotor and stator from the moulds	45min	45min	2	2
Welding	6h	4h	2	1
Blades assembly	2h	2h	3	3
Final assembly	1h30min	1h25min	2	2
Total	33h21min	16h18min	3	3

Figure 43: Time and people needed, comparison of the two methods

This table summarizes the entire time and people required for every step of the manufacturing process. It is important to precise that the numbers presented here are only indicative. Indeed, those numbers can vary a lot in function of the material used, the experience and the motivation of the team, the number of problems getting confronted to….

Nevertheless, it appears that the changes realized within this internship allow a huge time saving, it is observed that only the longest steps of the process have been reduced, and the total time of construction can be divided by two.

According to those numbers, it seems now that the manufacturing process of the turbine could potentially be reduced to one day. To allow that, it should be considered that spare CNC flat pieces and blades are always available and therefore, the construction would start with those pieces already carved. The pieces used could then be printed and replaced while the turbine is being build

VII) Open source data

According to the spirit of the book "Build your own wind turbine", the files created should be available on an open source format. It is important that anyone can access the files and use them for their own projects. It is indeed how the large community of Hugh Piggott small wind turbine builder has evolved and has improved itself so far. Therefore, the files have been also created on FreeCAD. Anyone can access the different pieces and check dimensions, shapes and quantities of every part useful to build the turbine. Below, the same piece as the one observed from Solidworks, figure 4, Is observed on FreeCAD.

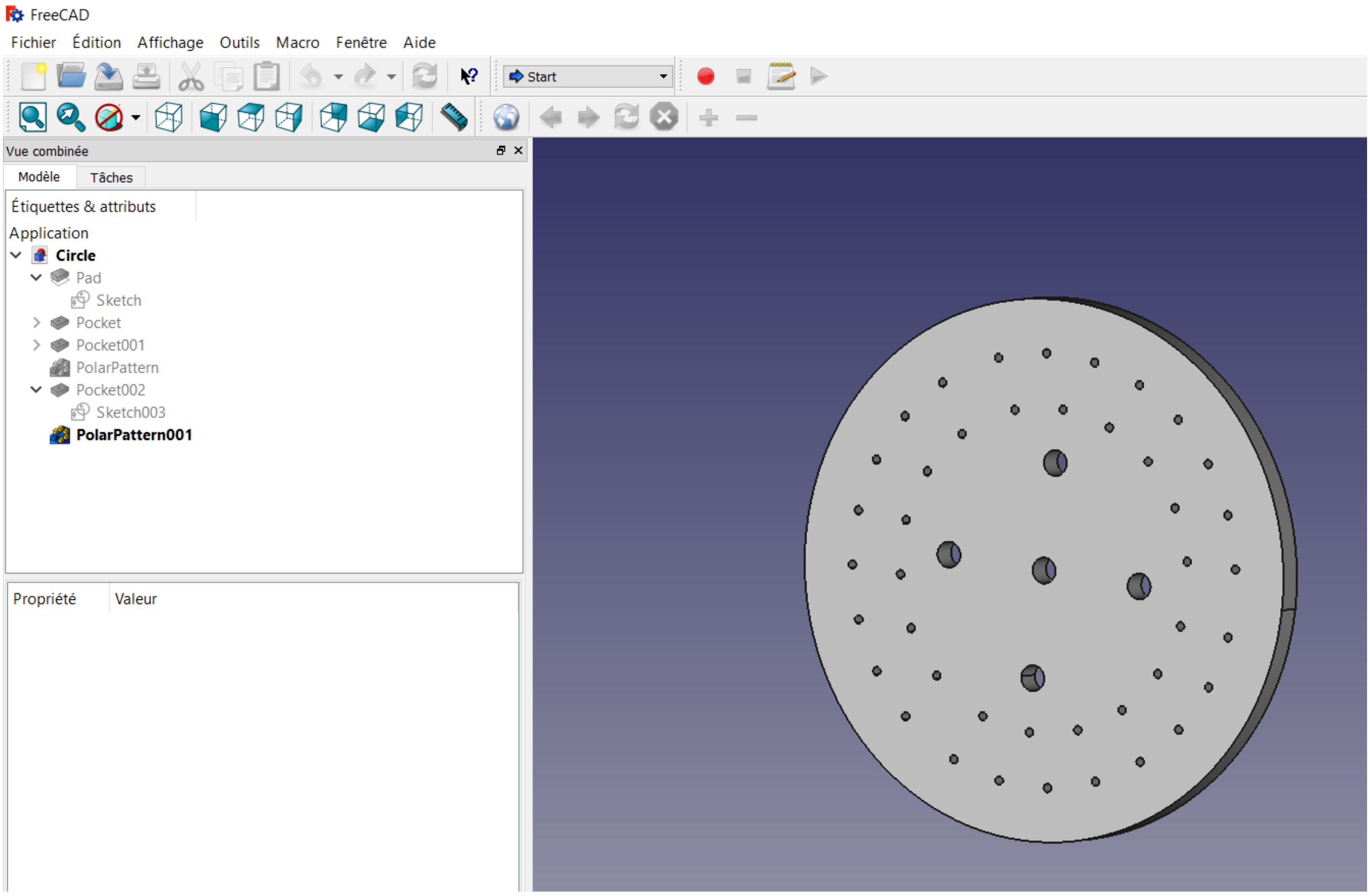


Figure 44: Piece example on FreeCAD

However, for esthetic and assembly reasons, for the creation of educational resources such as CAD videos and demos, the version designed on Solidworks should be used.

Conclusion

A new aspect in the construction of small manufactured wind turbine has been considered and experienced. This method turns out to be quicker and simpler to perform. More money must be invested in the construction but it can easily be interesting at an industrial scale.

It has been a very interesting and fulfilled experience to follow a wind turbine construction from its CAD design to its final achievement. It gives a greater understanding of the different steps followed from Hugh Piggott's book.

Sharing experience in the manufacturing process of a turbine is very interesting to understand better the construction and to enhance the quality of the final product. What has been acquired during this internship will be presented to ACE to expand the knowledge of the association and improve the teaching quality of its members. Perhaps the work realized will inspired other students to carry out their own projects.

Also, this method permits to short out significantly the amount of time required to perform a construction teaching course. As the steps of construction are still very similar to the original method, the persons learning from this course wouldn't miss any essential step or information required to achieve and understand the turbine.

Besides, the results shown here will be presented to NTUA, which, after complementary studies, will be shared to OSE and will help them in their researches on Global Village Construction Set.

Finally, bringing down the time of construction of such a wind turbine to 1 day can be a solution to answer almost instantaneously to a small energy demand in remoted location. A grid damage in a village for instance.

To go further

The project will then be extended to the other types of wind turbines presented in Hugh Piggott's book. Around five people will gather to create on FreeCAD the model of the 6 turbines described in the book. For educational purposes, as the model presented here, the movement of the turbines would be left free on the CAD file to create short animations.

Following the method presented, a small wind turbine construction kit could be created at a low price, it would include every piece required already printed out, the blades already carved, the product to mold the resin, the screws, bolts and nuts and a small guide to assemble it.

Literature Review

* « **Contruire Une Eolienne** » *Reseau Tripalium, Hugh Piggott,* French version 2015

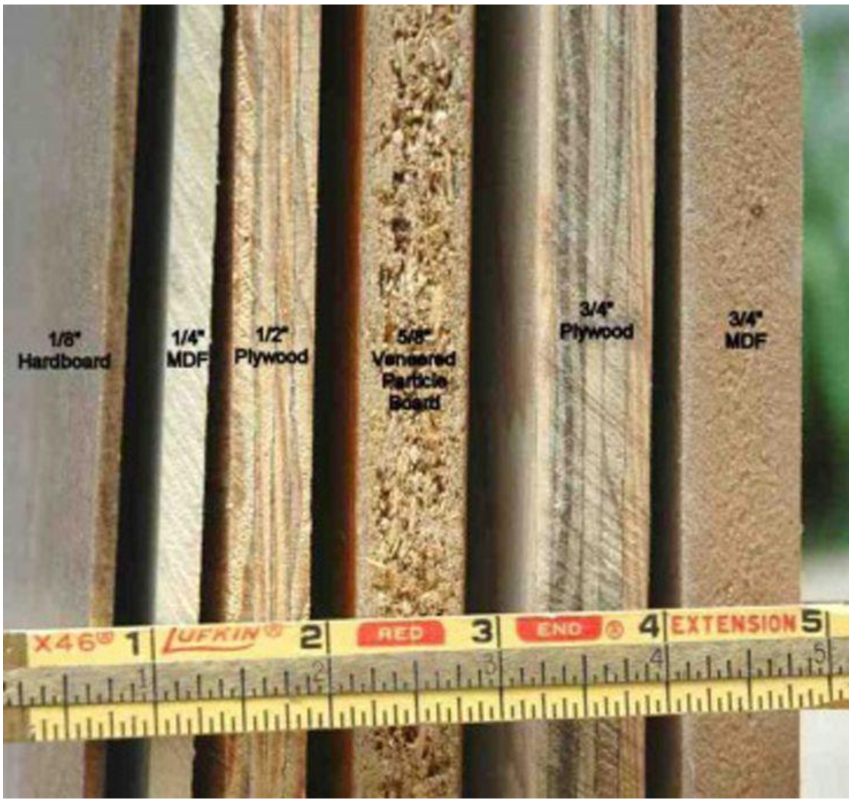
* "**A wind turbine recipe book**" *Hugh Piggott,* Jan 2009

* "**How to build a wind turbine**" *Hugh Piggott*, 2005

Appendices

2.4m Wind turbine, list of the required components

SWT plywood (birch) 6mm & 12mm thickness



Tail:
50cm x 120cm @ 6mm – 1 piece

Hub:
circle - 25cm x 25cm @ 12mm – 1 piece
triangle - 35.7cm x 35.7cm @ 12mm – 1 piece

Blade template:

20cm x 120cm @ 6mm – 1 piece

Coil winder:
12cm x 12cm @ 12mm – 3 pieces

Magnet template:
30cm x 30cm @ 6mm – 1 piece

Rotor moulds:
base – 40cm x 40cm @ 15mm – 2 pieces
can make this: base – 40cm x 40cm @ 12mm – 2 pieces
middle – 40 cm x 40 cm @ 18mm – 2 pieces
can make this: middle – 40cm x 40cm @ 12mm – 2 pieces
and middle – 40cm x 40cm @ 6mm – 2 pieces
lid – 40cm x 40cm @ 6mm – 2 pieces
island – 16.6cm x 16.6cm @ 10mm – 2 pieces
can make this: island – 16.6cm x 16.6cm @ 12mm – 2 pieces

Stator mould:
base and lid – 60cm x 60cm @ 15mm – 2 pieces
can make this: base and lid – 60cm x 60cm @ 12mm – 2 pieces
middle – 60cm x 60cm @ 13mm – 1 piece
can make this: middle – 60cm x 60cm @ 12mm – 1 piece
island – from middle part

2400 SWT Enameled Copper wire (magnet wire)
3kgr OD1.5mm (or two barrels of 1.5kgr for 24V stator)

2400 SWT Blades

Planned Pine @ 1.23m x 125mm(minimum) x 40mm(minimum) - 3 pieces (or 4 pieces) Make sure organizers understand that this is a minimum and they can get bigger

Rotor disks
Φ30cm Outside Diameter 8mm thickness (needs to be hot dip galvanized after it is cut) steel disks with appropriate wholes for bearing and hub (see sketch) – 2 pieces **NOTE: all metals are iron not stainless steel**

Bearing hub
Trailer hub with 4 bolts (min for 250kgr) Buy this first in order to get PCD and stud whole diameter

or car wheel hub with 4 bolts (min for 250kgr) Buy this first in order to get PCD and stud whole diameter

Casting materials
Vinyl Ester resin – 6kgr (maybe this is too much, 3-4 would do)
Catalyst for 6kgr of resin - 100gr
Talcum powder – 3kgr
Resin wax or vaseline
Fiberglass of 300gr – 2 pieces of 60x60cm + 2 pieces of 40x40cm

Magnets
46x30x10mm Neodymium N40 magnetized through thickness (black epoxy coated or nickel) – 24 pieces
Maybe buy 1or 2 more

Stainless steel parts
screws for hub 5mm x 30mm – 65 pieces
screws for fastening balancing weights 5mm x 25mm – 10 pieces
threaded rod M14 x 1m – 2 piece
threaded rod M12 x 1m – 1 piece

M14 nuts – 33 pieces
M14 small washers for regulation – 12 pieces
M14 wide washers for hub – 8 pieces
M12 nuts – 21 pieces
M12 small washers – 11 washers

Galvanized Screws & bolts for coil winder
M10 threaded rod x 1m – 1 piece
M10 nuts – 10 pieces
M10 washers medium size – 5 pieces
4 nails - long (5cm min) 5mm thick
10cm plastic pipe with internal diameter 10mm or more

Galvanized Screws & bolts for moulds
Stator fastening bolts M12 x 60mm – 20 pieces
Stator fastening wide washers M12 – 40 pieces
Stator fastening nuts M12 – 20 pieces
Stator screws 5mm x 25mm – 20 pieces
Rotor fastening bolts M14 x 50mm – 4 pieces
Rotor fastening wide washers M14 – 4 pieces
Rotor fastening nuts M14 – 4 pieces
Rotor screws 5mm x 30mm – 20 pieces
For stator soldering and mould 5mm x 40mm

Spacing washers
1mm thick M14 – 8 pieces
0.5mm thick M14 – 8 pieces

Electrical parts
Connection box 7cm x 7cm – 1 piece

Electrical conduit OD20 x 1m – 1 piece

Connector for OD20 conduit to go on connection box – 1 piece
Bolt cable lugs 6mm2 – 4 pieces

Electrical cable 1x6mm2 x 3m – 1 piece
Heat shrink for 6mm2 cable lugs x 1m – 1 piece
Heat shrink for stator connections 5mm(min thick) x 1m – 2 piece

3 electric tape rolls
1 bag of small cable ties (max 15cm long)

Metal parts - NOTE: all metals are iron not stainless steel
50 x 50 x 5mm Angle |_ x 95cm length
Tube Outside Diameter(OD)60mm (diameter) x 30cm (length), 3mm minimum thickness
Plate 90mm (length) x 90mm (width) x 10mm (thickness)
Plate 75mm (length) x 54mm (width) x 10mm (thickness)
Flat Bar 8mm (thickness) x 30mm (width) x 30cm (length) – 2 pieces
Flat Bar 8mm (thickness) x 40mm (width) x 30cm (length) – 2 piece
Flat Bar 5mm (thickness) x 30mm (width) x 30cm (length) – 1piece
Tube OD48mm x 1m (length) – 1 piece, 3mm minimum thickness
Tube OD60mm x 15cm (length) – 1 piece, 3mm minimum thickness
Plate 70mm (length) x 70mm (width) x 10mm (thickness)
Tube OD48mm x 25cm (length) – 1 piece, 3mm minimum thickness

left over pipe OD 60 or 48mm and plat plate 5mm thick for coil winder

NOTE: all metal plates and tubes will be cut to the correct size during the course. You just need to get hold of larger pieces of the appropriate materials.

General materials and consumables
Epoxy metal glue for magnets – 1piece or super glue

1 box of 3.2 welding electrodes
1 box of 2.5 welding electrodes