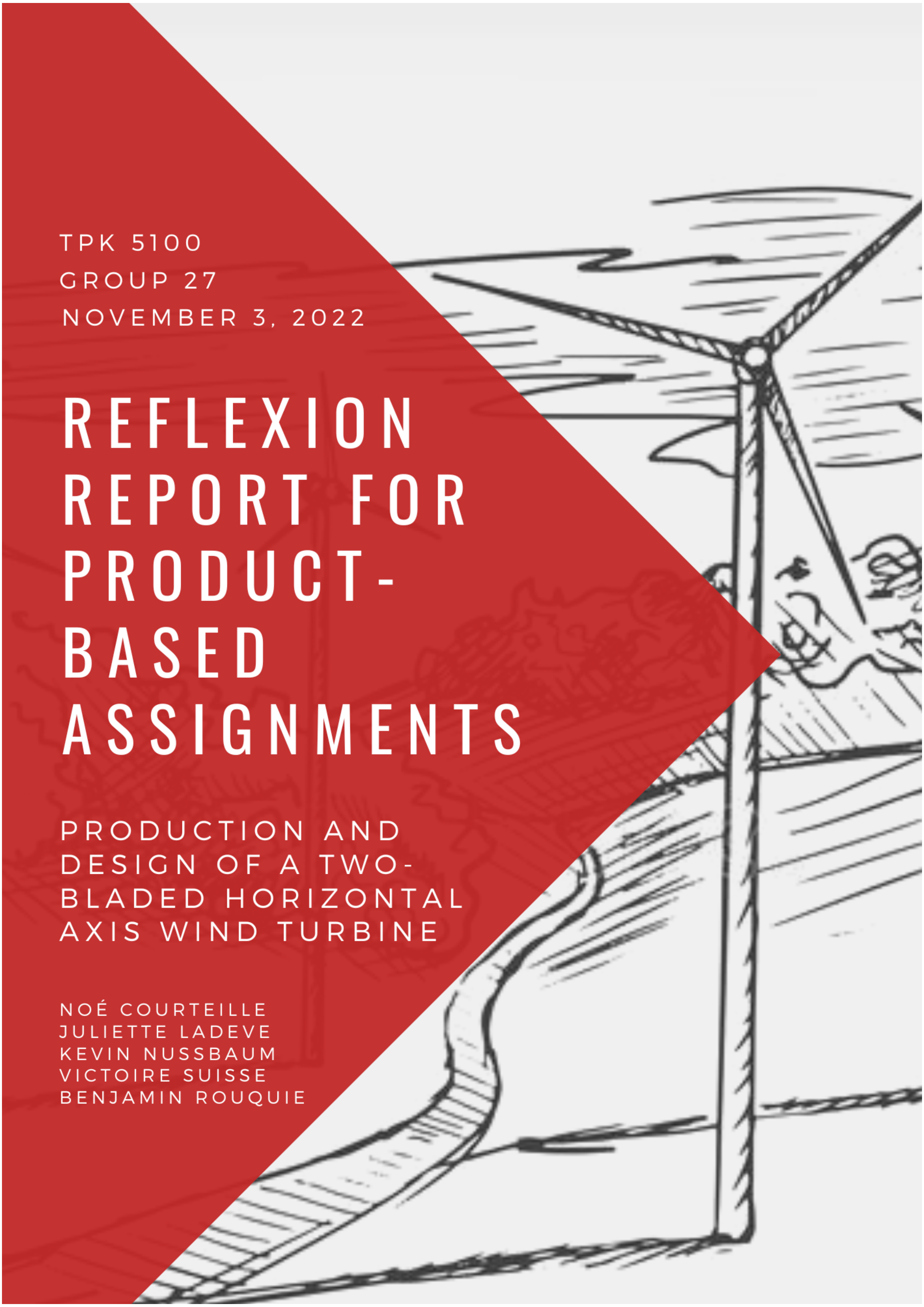

TPK 5100

GROUP 27

NOVEMBER 3, 2022

# REFLEXION REPORT FOR PRODUCT-BASED ASSIGNMENTS

## PRODUCTION AND DESIGN OF A TWO-BLADED HORIZONTAL AXIS WIND TURBINE

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# 1. Introduction

From a design idea to its production...

The project consists of the design and realization of a double horizontal axis wind turbine blade (HAWT) as well as the manufacture of its generator. The customer wants a study on the best performance criteria for two-bladed wind turbines in order to obtain maximum electricity production and has requested a qualitative and quantitative analysis, as well as the production of the device. Various tools will be used to model and program the elements of the project and an experiment in real conditions (wind corridor) will be carried out to test the performance of the final device. The final product to be manufactured will be a two-bladed horizontal axis wind turbine (HAWT) scale model. The wind turbine blade will be made from a 3D printer made of PLA material which is a non-toxic biodegradable plastic. The generator will consist of a rotor (2 or 4 poles) and the stator will be three-phase (3 phases). The prototype will be manufactured from wires and mechanical elements made available for study by the customer.

At the end, the client will receive a report outlining the design choices and assumptions considered for the design and modeling, calculations and performance curves produced by the ASHES software to obtain the ideal energy yields, the modeled parts (CAD Part), as well as a generator and a 3D blade.

# 1. Evaluation of Project management effort

In this part, an overall assessment of the efforts made by the group will be carried out. This will highlight the points of light and shadow that made it possible to advance or delay the project during the semester and analyze the project management used.

## 1.1 Organization of the group

In order to start the project as well as possible and move forward in the most efficient way, the group had to organize itself and divide up the work tasks. Very quickly, all the members of the group found their place on a task that suited them. The project was drawn up in different parts:

- The technical, calculatory, modeling and design part (Blade and generator)
- The construction part of the prototype
- Project management

The project management part as well as the construction of the prototype was carried out by the whole team because these are keyand essential elements that could notbe done individually. For project management, an agenda was made for each meeting that was organized in order to move forward more quickly and efficiently during the meeting moments. This was a very good way, really effective in order to be the most efficient. Noé and Benjamin made sure that the provisional schedule was well respected and that the tasks were done over time so as not to encroach on the next one at the risk of postponing all the tasks and having a problem when making deliverables.

For the design part, two teams were formed, Juliette and Victoire took care of the blades while Noé, Benjamin and Kevin took care of the generator in parallel.

On this step, we encountered more difficulties from an organizational point of view because the blades had to be modeled before the generator and it was only from a certain step that the two could be made in parallel. Indeed the generator depended on important parameters that were determined beforehand (eg Active length of coil, Diameter of the copper wire, etc.). A program was made in order to know what had to be carried out in what order which brought a lot of clarification and then allowed us to move on to the production part of the prototype all together. We made sure that the whole group was present for the construction part of the generator and the 3D printing of the blades because this is the culmination and the most concrete part of the project. The same applies to the performance test carried out in the wind corridor.

| Scale | Strongly Disagree | Disagree | Neither agree nor disagree | Agree | Strongly Agree |
|---|---|---|---|---|---|
| Your response | | | | | X |

### 1.2 Project Risk Management Plan

In order to have the best possible project management and to ensure the smooth running of the project, a risk analysis was carried out and five risks were identified. The latter had been classified in the matrix according to their probability of occurrence as well as their severity. A prevention plan was then developed to reduce these two factors (occurrence and severity) and bring them into an acceptable management area. This tool was of great service to us because we were not slowed down by one of these risks throughout the project, each step being anticipated while taking into account their risks and implementing effective management tools to mitigate them. These risks mainly concerned the project management and prototype design stages.

| Scale | Strongly Disagree | Disagree | Neither agree nor disagree | Agree | Strongly Agree |
|---|---|---|---|---|---|
| Your response | | | | | X |

### 1.3 Communication plan

Two modes of communication had been identified, internal communication and external communication. From an internal communication point of view, which we felt was the most important, we are very satisfied with the way this was managed. The tools at our disposal that we had decided to use (Blackboard and Whatsapp) were very useful and allowed us to communicate easily and in the most fluid way possible. Along the way, we added an internal communication element the, sharepoint ,that allowed us to have a fluid interface and to follow all the dates for the deliverables as well as the different assignments. This management tool was added at the beginning because we quickly noticed that we could be overwhelmed by all the deadlines imposed on us. For external communication, we decided to create a logo and a communication brochure. The communication brochure brought us some trouble because it was difficult to synthesize so much information on so little space and manage to convey what was most important for future customers.

| Scale | Strongly Disagree | Disagree | Neither agree nor disagree | Agree | Strongly Agree |
|---|---|---|---|---|---|
| Your response | | | | X | |

## 1.4 Deliverables and Success Criteria

From a general point of view, all the deliverables and objectives that have been defined according to the different success criteria have been achieved. This can be explained by several points:

- No delay was taken on the project which allowed us to reach the end on time and to face the slight problems that we could encounter for example during the modeling and design phases
- The tasks were distributed equitably, taking into account the workloads of the entire team and the skills of each, which allowed us to move forward efficiently.
- The definition of the client's needs, as well as the stakes were carried out in a clear and precise way from the beginning which allowed a better understanding of the project.
- The whole team was able to stay motivated and invested throughout the project and despite the moments of doubt, there was always a person to remotivate.

We can therefore consider that the final result to be produced was respected according to the initial plan and few deviations are to be noted except as explained previously on the management of the conception and design phase which proved to be more complex than expected.

| Scale | Strongly Disagree | Disagree | Neither agree nor disagree | Agree | Strongly Agree |
|---|---|---|---|---|---|
| Your response | | | | X | |

## 2. Evaluation of the impact (Project success)

For this part, we will ask about the evaluation of the impact and significance of our final product, i.e. a generator and a two-bladed horizontal axis wind turbine (HAWT). The idea is to determine if the product will create value for the user and which evaluation we are giving.

### 2.1 Target audience

This project seeks to reach different targets, both companies working in the wind energy sector as well as potential investors. Indeed the project consists in the realization of a two-blade wind turbine which is not a conventional model of wind turbine (generally 3 blades) and which therefore stands out from the onshore wind market. Indeed, if the result of the study shows that the effectiveness of the product according to its manufacturing cost is profitable, many customers will be interested.
The idea is therefore to approach recognized companies in the sector (e.g. Enercon, Ostwind, Engie, Equinor ASA ...) in order to submit the project to them and so that they can buy our project and thus realize it. Indeed our group could be compared to a design office and we are therefore not sufficiently competent and do not have enough means to carry out the various studies and build these prototypes on a full-scale . This is the main customer, with onshore and offshore wind taking a growing place in the global energy mix, which is now seeking to detach itself from fossil fuels, which are exhaustible resources.
The second customer who could be the target of our product would be potential investors, banks and partners who could support our project and potentially invest in it. We provide them with in-depth technical studies that will build on the solidity of our project and will subsequently convince the major global companies mentioned above.
In both cases, we will provide all the plans, models and technical studies that will be there to support our project. A brochure has also been included in the communication plan to support the project with these future clients.

### 2.2 Final product

Different criteria can be taken into account in order to evaluate our final product.
The first that is most important to us is customer satisfaction. Indeed all the work revolves around that knoxledgewe had to meet a specific need. We had to make a technical report, the 3D modeling parts and the prototype made (Pale & generator) and following the evaluation of these renderings by

our client, the latter provided us with very positive feedback on the work done. For us, this is the biggest achievement and success of the project. A happy customer means a successful project.

The second success criterion corresponds to the test phase we carried out on the final prototype. This test phase was divided into two parts, the first which corresponded to the test phase of the generator which allowed to see if the design had been well done, that we had made the right technical choices and that an electromagnetic current was well induced. We have recovered the various parameters, graphs (Flux density, Induce voltage, Generator efficiency, Synchronous reactance, Volatge....) that agree well with the analytical analysis carried out beforehand. Following these very positive results, we were able to carry out the second test phase which consisted of introducing on a device previously created the generator as well as the wind turbine blade and testing their performance in a wind corridor. The goal is to obtain the most important efficiency (knowing that the power coefficiency can not be greater than 60% also called the Betz limit). Following this test phase, we obtained a power coefficiency of 53.4% which is very good considering the margins of error due to the artisanal realization ofthe generator.

Of course the prototype was made by hand which leaves room for a number of uncertainties especially for the generator or the coils. By realizing the relative errors, we obtain percentages between 15 and 3% which is more than acceptable. (Relative errors are very good when they are below 10% and acceptable when they are below 20%. )

A third criterion for success is to compare our results to what already exists. Indeed our goal is to make a high-performance product. By comparing it with existing products on the market, it is possible to situate its performance. For this purpose, a benchmark, i.e. an analysis and comparison of other competing and market-leading products , was carried out.

Finally, our final criterion for success is if we are satisfied with what we have achieved and have enjoyed doing this project. The general feeling that emerges from the project is very positive since we all had fun, despite the difficulties encountered at times and we all greatly enjoyed this beautiful project.

| Scale | Strongly Disagree | Disagree | Neither agree nor disagree | Agree | Strongly Agree |
|---|---|---|---|---|---|
| Your response | | | | | X |

## 3. Factors that have contributed to failure / success.

In this part, we will look at the different factors that contributed to the success of the project, see which ones are the most significant and in what way.

We identified 6 factors that we felt were most relevant to the success of our project.

The first was the correct analysis of our **client's need**. We knew exactly what he was waiting for, in which direction he would go, and the purpose of the project was clearly stated. A project seeks to achieve a goal that is to say the intention and aspiration around it and the steps to access it correspond to the different objectives to achieve this intention. Afterwards we were able to properly divide the project and set ourselves milestones to meet the different deadlines.

In a second step, an essential element for the success of a project is the respect of the **golden triangle** (Quality, Costs, Deadlines). It is the responsibility of the project manager who is responsible for ensuring that these criteria are met. These three elements are linked in one way or another and an alteration of one of these pillars affects the others and in turn the project as a whole. We have continuously kept these three notions in mind which has allowed us to achieve the success of our project. For a successful project, a balance must be maintained between these three pillars. Indeed, it is impossible to have a project with low costs without losing quality or lengthening the deadlines for example.

From a technical point of view, all the roles and tasks assigned throughout the duration of the project were carried out according to the **skills of each**, its strengths, its weaknesses which allowed to move forward effectively. As mentioned above, the technical studies were divided into two teams (Blade and generator), however the practical part of making the prototype was done in groups so that everyone could acquire these new skills and understand how the prototype works.

One factor that we think is also important is **communication**. It is both internal within the team, and external with the client. Indeed, throughout the progress of the project we kept the client and the stakeholders informed so that they knew the progress of the project and the changes or problems that may have occurred. It also allowed us to quickly clarify the grey points that we could have with our customer and thus move faster. Within the team we also ensured that communication was important with open communication channels like WhatsApp and regular meetings.

During any project, changes happen quickly, and one factor that has partly ensured our success is the **adaptability** of the whole group. Whatever the planned planning, there are always unforeseen circumstances that have been omitted. (ex: The initial code platform was matlab but the client finally forced us to use python). The team quickly bounced back and changed platforms, but this detail had not been taken into account before. This could have been a factor in the failure of the project if we had not realized it early enough to make the change. Fortunately, with the communication put in place and the many points made with the client, the shot was quickly rectified.

A final important element is the consideration of **feedback**. After each of our meetings with our client, the latter gave us feedback on the possible improvements, the changes that needed to be made. Each return is to be taken into consideration and has been modified thereafter in order to be as close as possible to what the customer expected. It also allowed us to initially question our method of communication following the coding platform incident and to do what was necessary to ensure that this did not happen again later.

## 4. Most important lessons from your project

In this part we can learn different important lessons that have been paramount to the success of this project and that can be applied to any type of project management.

First, the key point is to identify and define the need, to know what the customer wants both technically and functionally. Do not have an unspoken that could delay the smooth running of the project. Do not hesitate to make a questionnaire with your missing data if necessary to provide later to your customer. Don't forget to define a project manager to manage your team as best as possible. Managing is managing yourself and leading a team.

Once this need is defined, it will be necessary to break down the different tasks, define the different roles in this project (Actors, Consulted, Informed, Customer ...), the organization in the form of planning without forgetting to define the budget (if your client asks you for a prototype or to quantify your cost). All these steps will allow you to prepare & frame your project.

Our advice would be to use different project management tools such as the SMART method, WWWWHW method (Identification of needs), PBS, WBS (Task division), perform a PERT or a GLOVE (Planning) or use the RACI method (Roles). A successful project is one that meets the following three criteria: Quality, Costs, Deadlines. The different tools mentioned above will allow you to achieve this.

We learned that in order to be as effective as possible during meeting sessions, the realization of an agenda makes it possible to sweep all the topics without omitting them and thus to gain efficiency. The meetings are then guided by the project manager who makes it possible not to scatter in all directions. The next objectives are defined and the tasks are distributed according to the provisional schedule.

Communication within the group is also essential, every word in the group is to be considered and taken into account. No remark is stupid because most of the time it brings a point of view or a reflection that had not been raised before. Take the time to listen to yourself, without cutting yourself off, you will see that you will move much faster afterwards.

Our experience suggests that meeting regularly to make adjustments allows us to move faster, correct the points that are wrong and rectify the step quickly. It is then easier to work on the technical part on your side if you have previously identified the skills of each. Do not hesitate to do team building together to weld your team, you will then feel more comfortable and it can only advance your project.

# 5. Reflection on learning and unlearning

## 5.1 Knowledge needed to meetthe project's emerging needs and challenges

This project was for the entire team an important element in the construction and management of a project from start to finish, an essential element today as a project manager or for our future life as engineers. Throughout this period, we have learned to work as a team, to know how to listen to each other, to take everyone's opinions to progress. We have also acquired technical knowledge from an engineering point of view with sizing methods and software that were previously unknown to us. This learning (e.g. ASHES, INVENTOR) was carried out in self-training using different videos, test phases and allowed us to master the software perfectly to master all the parameters. So we knew which parameter to modify to obtain this or that data in order to have the best possible yield. This allowed us to acquire autonomy, a certain rigor also because on such a meticulous project, no parameter can be left to chance. We have also worked on our ability to adapt to changes to be made in a relatively short time and the difficulties encountered for certain technical parts.

From the point of view of the knowledge acquired, we can mention project management, which is the essential element for the proper conduct of the project as well as the various management tools (WBS, PBS, Gantt, Risk Matrix, etc.). We also learned or deepened our knowledge of programming languages (Python and Excel) as well as different modeling software (ASHES and INVENTOR). We have acquired a lot of knowledge about the design and operation of wind turbines and learned to meet with practical challenges and consolidated our knowledge in thermal power and electromagnetism. From a practical point of view, at the end of the project we realized that we had acquired a certain autonomy in order to meet the deadlines and the various milestones that we had set on the Gantt chart.

All these elements allowed us to carry out this project that we particularly appreciated.

## 5.2 Unlearned elements during the project in order to manage emerging problems/questions and challenges

This part is more complex to answer because the project has brought us more than we unlearned. Nevertheless we can identify a few points.

At first, we were a group where no one knew each other, so we had to adapt and not impose our way of managing a project as we were taught in our respective schools. Each teaching method is different and you have to adapt. It was quite beneficial to us in the end because it brought us more as a group because we were leaving on a neutral basis.

In a second time, for most of us our knowledge of electromagnetism went back 2 or 3 years and was therefore erroneous or forgotten. It was therefore necessary to relearn and review this information in order to be as accurate and accurate as possible from a technical point of view.

## 6. Acknowledgments

We would particularly like to thank our teachers for this support throughout the project and all the actors who made it possible. Their advice was of great help to us for the success and good management of the project.

We would also like to thank NTNU University for providing us with the necessary equipment for the construction of the prototype and generator) and for supporting us in the realization of this project.

# 7. References

Hussein, B. (2018). The Road to Success: Narratives and Insights from Real-Life Projects, Fagbokforlaget.
Raelin, J. A. (2001). "Public Reflection as the Basis of Learning." Management Learning **32**(1): 11–30.

# 8. Appendix

**Appendix 1: Link to the video :** https://www.youtube.com/watch?v=cLN9Sh2rnh8

2022
2023

TPK 5100

# PROJECT MANAGEMENT

## WIND TURBINE

Noé COURTEILLE
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MOULIN
À VENT

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Submission of the application

From a design idea to its production...

The project consists of the design and realization of a double horizontal axis wind turbine blade (HAWT) as well as the production of its generator. The customer wants a study on the best performance criteria for two-bladed wind turbines in order to obtain maximum electricity production and has requested a qualitative and quantitative analysis, as well as the production of the device. Various tools will be used to model and program the elements of the project and an experiment in real conditions (wind corridor) will be carried out to test the performance of the final device.

# 1. Analysis of the need

## 1.1. Horned beast

In order to better understand the need, a horned beast is made :

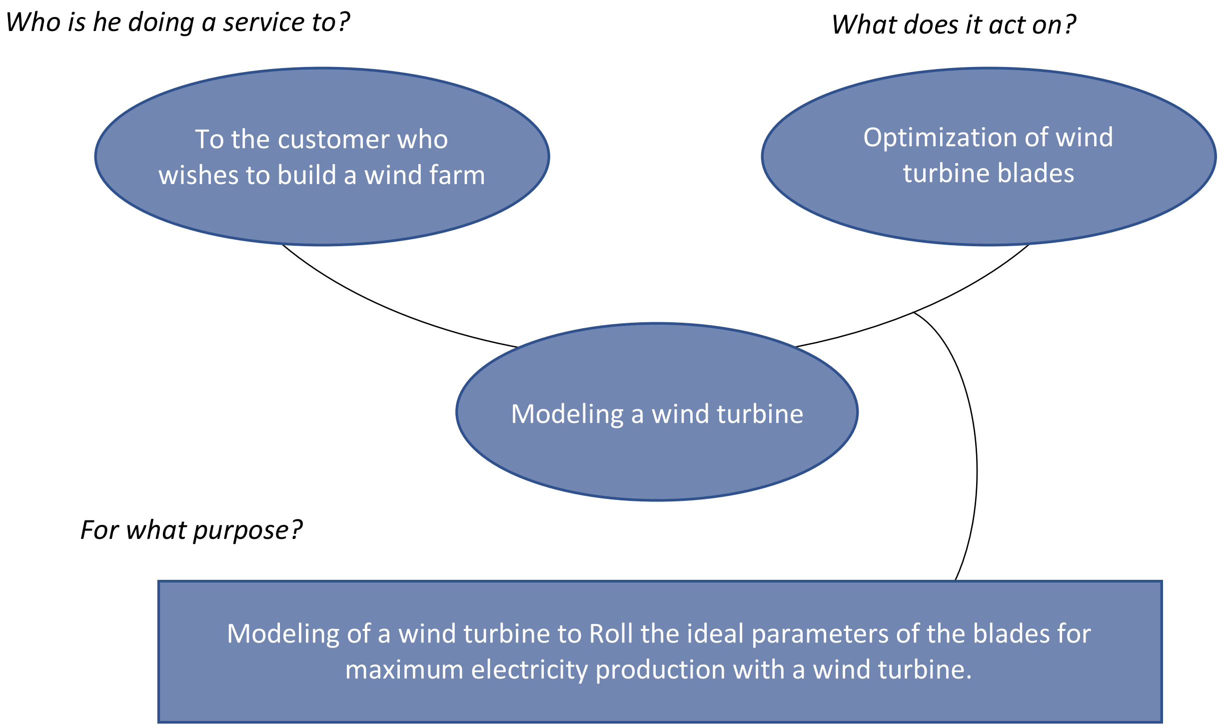



*Figure 1 : Horned Beast of Need*

## 1.2. Type of product to be manufactured

For this project, the final product to be manufactured will be a two-bladed horizontal axis wind turbine (HAWT) scale model. The wind turbine blade will be made from a 3D printer made of PLA material which is a non-toxic biodegradable plastic. The generator will be composed of a rotor (2 or 4 poles) and the stator must be produced with a choice of a single-phase or three-phase stator. The prototype will be manufactured from wires and mechanical elements made available for study by the customer.

### 1.3. Means used to produce the product

In order to best realize this product, a certain freedom was given for the modeling as well as the construction of the final product:

Imposed parameters: Dimensions 990 * 98 * 48mm for 3D printing, number of rotor poles (2 or 4), three-phase or phased stator

Free parameters: Choice of airfoil model, Design parameters (TSR, Radius, velocity, Reynold number, number element per blade...)

Modeling software: ASHES, Python, Matlab, Inventor, Excel

## 2. Presentation of stakeholders

In order to visualize the actors of this project, a stakeholder mapping was carried out. This mapping makes it possible to identify and position each of the actors who will participate in the realization of the project, to ensure the conformity of the product and to ensure that it meets the need stated by the customer.  It also makes it possible to organize the stages of project implementation according to each actor in order to respond more effectively to the specifications.

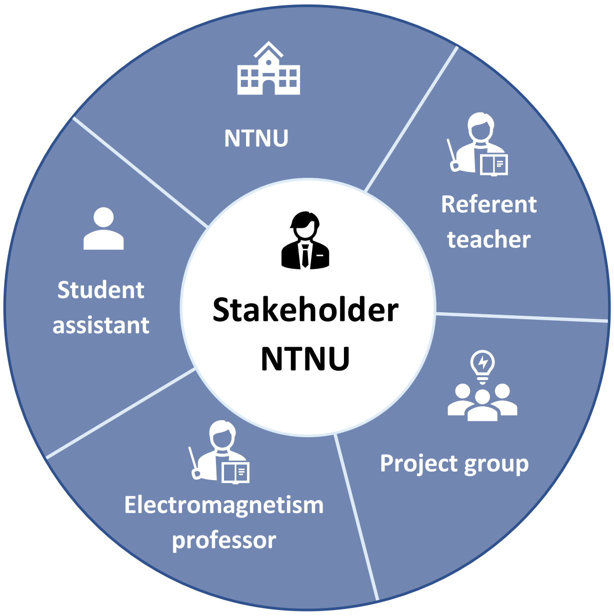



*Figure 2 : Customer Stakeholders*

In order to develop an effective stakeholder management plan, stakeholders must be clearly identified and evaluated. Stakeholders will be identified by carrying out an analysis of the latter in which relevant information (interest, involvement, interdependence, influence and potential impacts on the success of the project) is gathered, documented and analyzed. We therefore carry out a stakeholder analysis register.

*Table 1 : Stakeholder Analysis Register*

| Group name | # in Group | Description & Key attributes | Impact on project | Impacted by project | Current state | Issues, Opportunities and Risks |
|---|---|---|---|---|---|---|
| NTNU | 1 | School that supports the project, puts us the premises and its various equipment to carry out the production of the prototype. It is she who supports the project, so it is the main customer. | M | M | N | Tend to have a final project that will conclude the effectiveness of his training as an engineering student and the quality of teaching. |
| Referent teacher | 2 | Professor guiding us in the design and modeling of the project as well as in project management. Key role in the realization of the project and on the different knowledge of aerodynamics. | H | M | L | Success of the project in order to be able to repeat the project next year and builds on all the knowledge and mistakes of this year to improve it. |
| Project group | 5 | Set of 5 engineering students, hardworking, serious group. | H | H | L | Tend to the success of the project, risk of final product that does not work but a huge contribution of knowledge both in project management and technical knowledge on wind energy (aerodynamics and electromagnetism) |
| Electromagnetism professor | 1 | Professor giving us all the notions and basics of electromagnetism to apprehend the modeling, analysis and design of the generator | H | M | S | Opportunity to transmit knowledge within the framework of the project and tends to the success of the project. |
| Student assistant | 4 | Students present to help us at every stage of design in case of questions | L | L | S | Students in support of the project helping us to answer our various questions but not always having the necessary knowledge to support us in the project. |

Note that the impact is measured by High (H), Medium (M) or Low (L).

The current state will be evaluated according to the following criteria:

U – Unaware – this group has no information about the project

R – Resistant – aware of project and resistant to the changes and impacts the project may bring

N – Neutral – aware of the project and neither supportive nor resistant

S – Supportive – aware of the project and the potential changes and impacts and is supportive

L – Leading – aware of the project and actively engaged to ensure the project's success

This stakeholder management is an important process to effectively engage stakeholders throughout the project lifecycle, based on the analysis of their needs, interest and potential impact on the success of the project. Through these two analyses above, we get a clear and achievable plan to interact with project stakeholders.

# 3. Issues

## 3.1. Project Issues

There are different challenges for this project, first of all at the technical level:

- Acquire skills in modeling as well as electrical and mechanical sizing.
- Find criteria allowing the wind turbine to have a good performance.
- Successfully build the rotor and blade of the wind turbine and then assemble them.

There are challenges at the human level, indeed we are a team of 10 people, so we must succeed in organizing and distributing tasks according to the skills of each.

## 3.2. Skills

Throughout the project, different skills will be acquired, both technical and management. These will be acquired through the courses taught, group work as well as by the students themselves. This project will be perfect in order to best combine all the skills necessary for the management of a real and concrete project necessary for an engineer.

*Table 2 : Definition of acquired competencies*

| TECHNICAL COMPETENCIES | MANAGEMENT SKILLS |
|---|---|
| Mastery of numerical simulation software (ASHES, Inventor) | Team Management |
| Engineering and engineering | Project Management |
| Computer Science and Programming | Teamwork |
| Wind project development | Organization |

# 4. Results

As part of this project, two deliverables are expected: A technical report and the model.

The technical report will contain all the design steps up to the modeling of the prototype. It will explain in a simple and understandable way the choices made to build this model, the assumptions as well as the codes and calculations used. The expected result is to have modeled, sized and assembled a wind turbine blade and its rotor, all being to optimize the shape of the blade to maximize the amount of electricity produced by playing on the parameters of each section of the blade.

# 5. Purpose and objectives

## 5.1. Purpose of the project

The different purposes given by the client are as follows:

1) Give knowledge in designing an operating wind turbine
2) Deal with practical challenges
3) Use known and unknown software
4) Group work
5) Develop the "art of engineering gut feelings"

## 5.2. Objectives

The project management method that was used to define the project framework and the overall objectives to be achieved was that of WWWWHW (Who, What, Where, When, How, Why). It is an approach that consists in collecting all the relevant information available by asking a maximum of questions of all kinds to answer the given topic. The idea is therefore to think constructively in order to highlight the main causes of the problem, the reasons for being of the project, define the main lines of an action plan ...

This method makes it possible to have a first global overview of the project in its broad outlines, without neglecting anything.

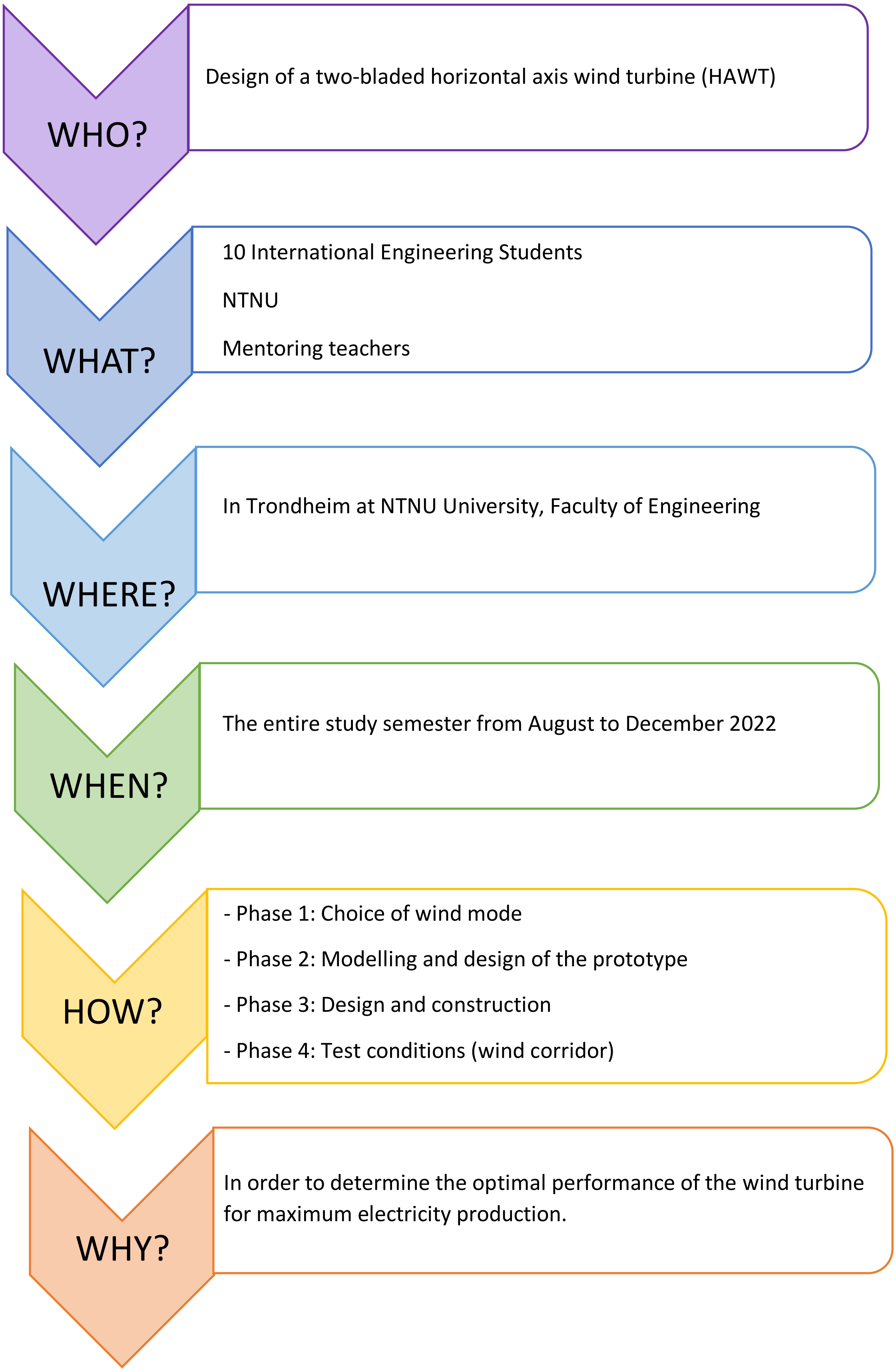



*Figure 3 : WWWWHW method*

# 6. Project Risks

## 6.1. Identify

In order to properly frame this project and ensure the smooth running of each step, a risk analysis was carried out.

The risks are broken down in the following table according to the type of resources they affect. We defined a scale of 1 to 4 to establish the probability of occurrence and the severity of the risk in question, 1 being the least likely and the least serious, 4 being a very probable or very serious risk.

*Table 3 : Client Risk Identification*

| RESOURCE | HUMAN BEING | EQUIPMENT | | | TIME |
|---|---|---|---|---|---|
| Risk | Lack of technicians in the team | Unavailability of some parts | 3D printer unavailability | Prototype breakage | Poorly estimated time |
| Probability | 2 | 4 | 1 | 3 | 2 |
| Forcefulness | 4 | 2 | 3 | 4 | 4 |
| Total | 8 | 8 | 3 | 12 | 8 |

## 6.2. Prioritize

To classify risks, they must be prioritized. Thanks to the assessment matrix, it is possible to identify the frequency and severity of the risk. We have put red dots to locate in the matrix the risks mentioned in the previous table.

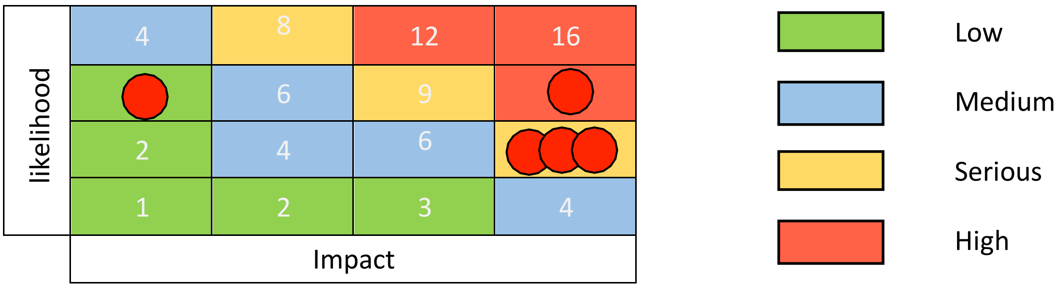



*Figure 4 : Risk Assessment Matrix*

## 6.3. Manage

After analysis of all risks, a prevention and/or protection plan has been drawn up in order to reduce the probability of risk occurring or also to reduce the severity of the consequences of the risk. They will be managed as follows:

- Lack of technicians in the team: *Ask student assistants*
- Unavailability of certain parts: *Have a reserve of spare parts and ensure the abundance of parts chosen during construction*
- Printer unavailability: *Printing blades with a CNC machine, Choosing multiple printing slots*

- Prototype breakage: *Protect prototypes when moving and be careful when handling it*
- Poorly estimated time*: Make progress reports regularly and rectify if the project is delayed*

Thanks to the prevention/protection plan, it is possible to reduce our risks in the acceptable risk zone of the criticality matrix :

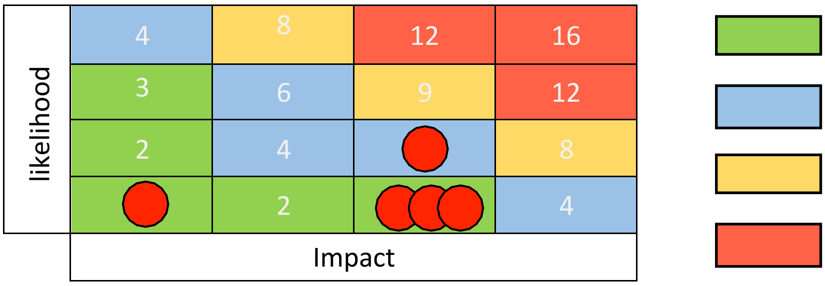



*Figure 5 : Managed Risk Matrix*

## 7. Key success factor

The smooth running and success of the project are conditioned by various factors:

- Understand the requirements and challenges of the project in order to propose the most appropriate solution.
- Maintain good communication and project management to be as efficient as possible and promote the success of the project.
- Stay in a dynamic of motivation and investment.
- Identify the skills of each team member
- Have a very good organization n (Use of a Gantt, WBS, project management tool ...) to work more efficiently


*Figure 6 : Key Success Factors*

# 8. Project Timeline

## 8.1. Project breakdown structure

To better understand the project, a PBS was conducted. It is an effective tool in the form of a product flowchart that is used to evaluate, plan and display the required results of the project. This will reduce the complexity of the project and provide a better understanding of the final product and its components.

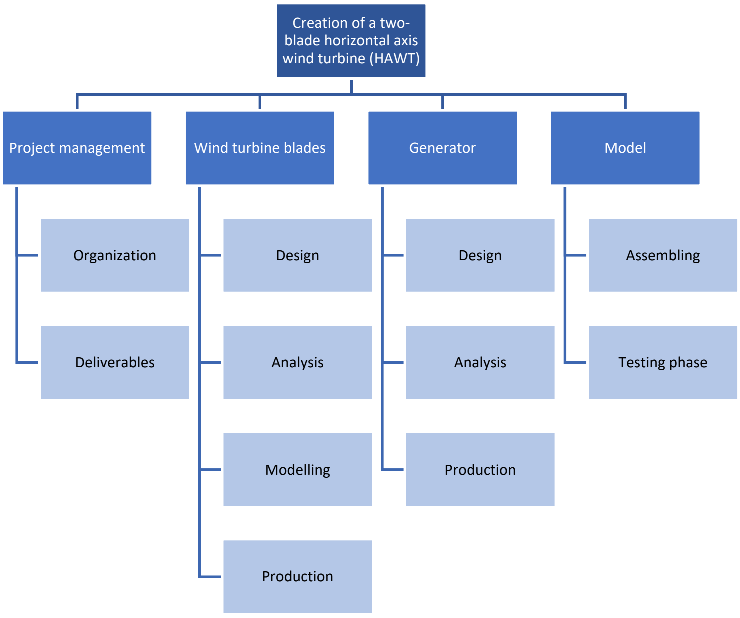



*Figure 7 : Project breakdown structure*

## 8.2. Work Breakdown Structure (WBS)

In order to facilitate the organization of the project and to obtain a better overall vision of it, a WBS was carried out. This makes it possible to divide the project into several lots and to assign to each of these lots the respective tasks as it is possible to see in Figure 8, four parts have been identified:

- Project management
- Wind turbine Blade
- Generator
- Model

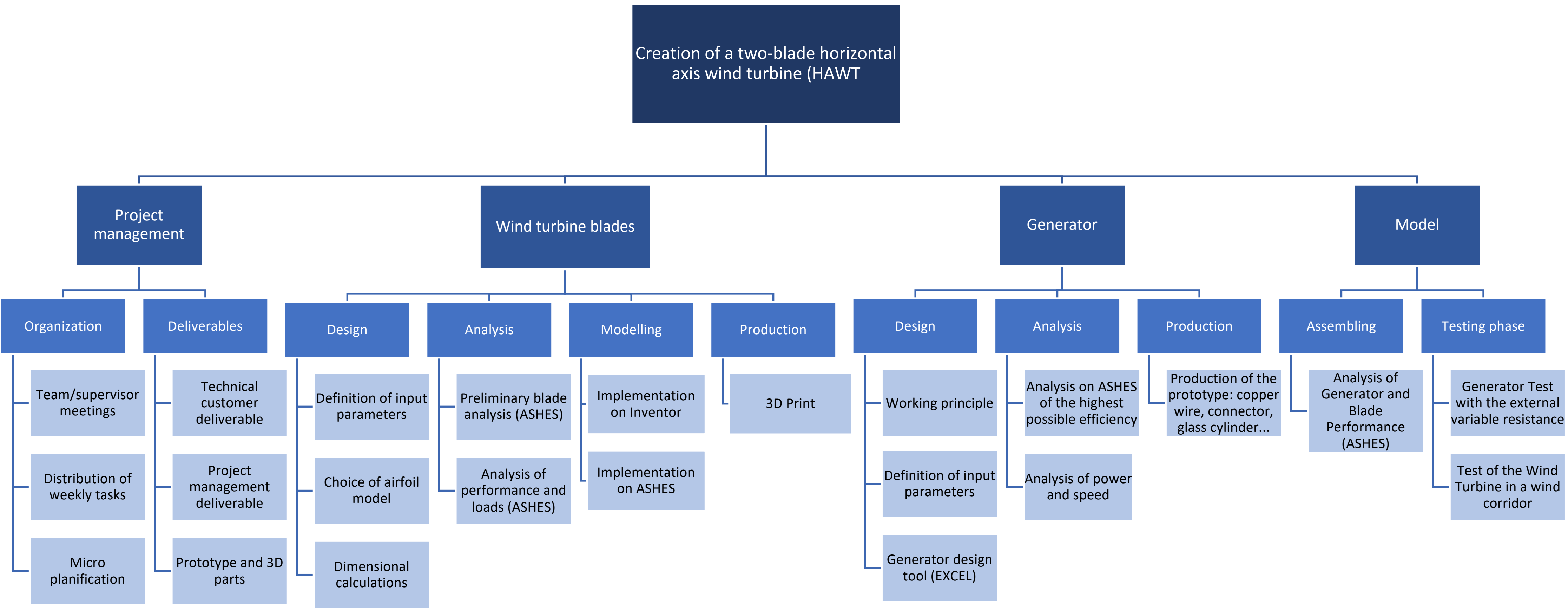



*Figure 8 : Work Breakdown Structure (WBS)*

### 8.3. Organizational Breakdown Structure (OBS) and inter-team distribution:

Thanks to the realization of the WBS, all tasks could be divided between each member of the team. This ensures a good division of tasks and better structures the execution of the project.

An inter-team distribution has also been carried out and on each stage, a member of the team will be responsible for its smooth running. The inter-team distribution was carried out according to the skills of each member.

*Table 4 : Inter-Team Distribution*

| Team Member | Role |
|---|---|
| **Noé** | Project manager, responsible for project management and technical study of the generator |
| **Benjamin** | Responsible for the technical study of the generator and project management |
| **Kevin** | Responsible for the technical study of the generator and the production of prototypes |
| **Juliette** | Graphic manager, technical study of the blades and test phase of the prototype |
| **Victoire** | Editorial manager, technical study of the blades and the test phase of the prototype |

Below are two overviews of the OBS on two different lots:

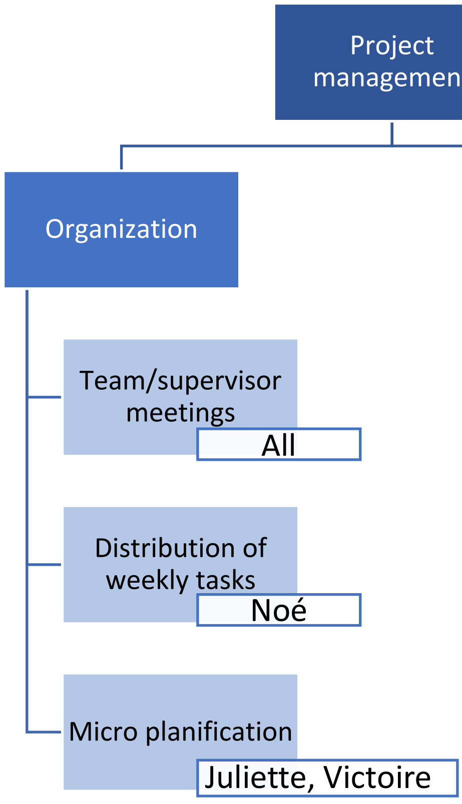



*Figure 9 : Subpart OBS - Project Management*

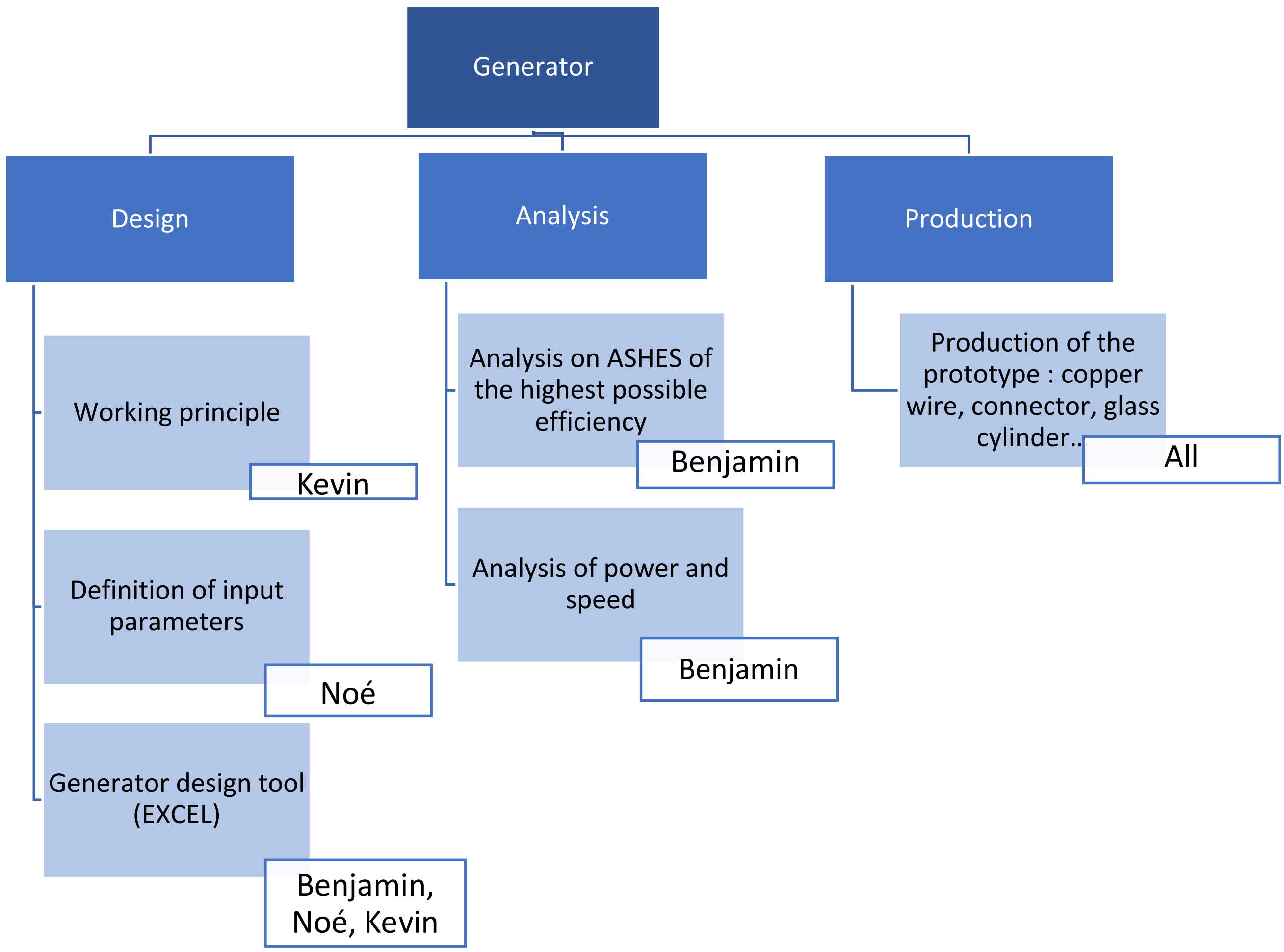



*Figure 10 : Sub-part OBS - Generator*

## 8.4. Micro-planning

For each of the steps listed above, a duration was determined based on the workload each represents. Below, the micro-schedule including these major steps.

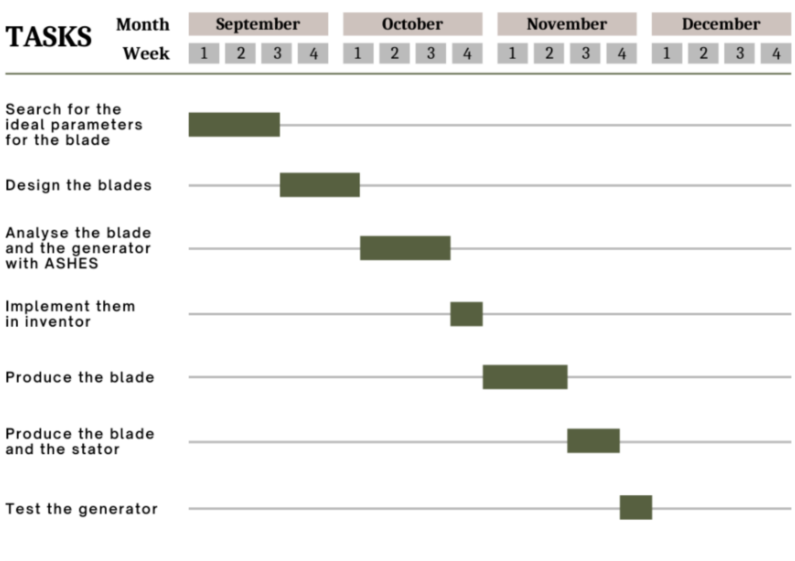
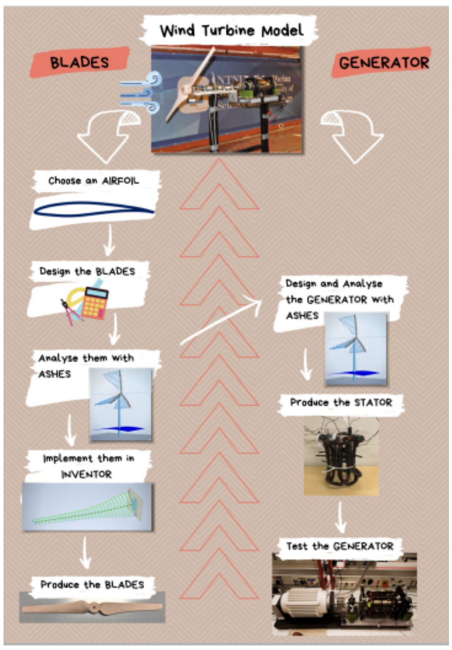



*Figure 11 : Micro provisional planning*



### 8.5. Estimation of the duration of each task (construction and production) of the project.

In this part, a network diagraph was produced. It is a graphical representation of all project tasks, responsibilities, and workflows. It allows to establish the schedule and the sequence of work of the project and is widely used to follow its progress through each stage, until its completion. There are two types of network diagrams in project management: The Arrow Diagram Method (ADM) and the Precedence Diagramming Method (PDM).

*Table 5 : Task Definition*

A: Choose an airfoil
B: Design the blades
C: Analysis them with ASHES
D: Implement them in INVENTOR
E: Produce the blades

F : Design and analyze the generator with ASHES
G : Produce the stator
H: Test the generator
I : Assemble and test the model

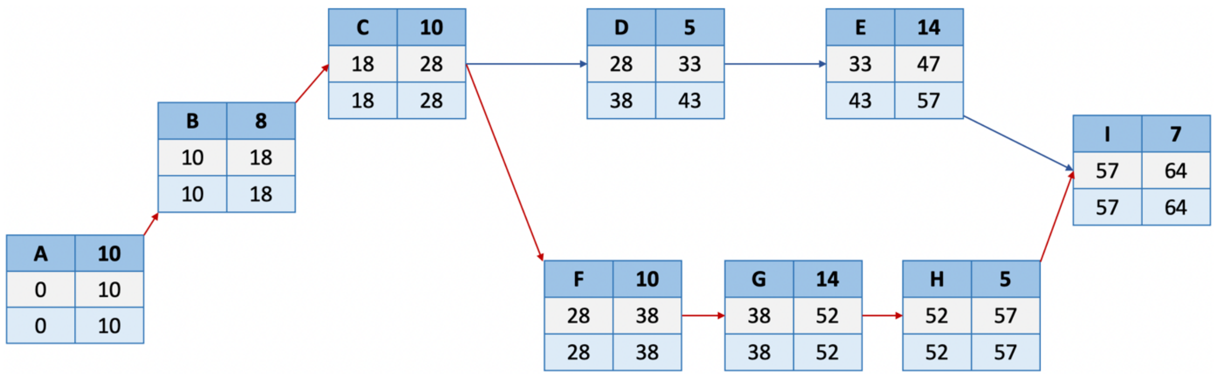



*Figure 12 : PDM Diagram*

This network diagram represents the sequence of tasks to be done during the project. The red arrows show the critical path, i.e., the tasks that need to be completed in time for the project not to fall behind.

## 9. Communication plan

### 9.1. Internal communication support

Internal communication is essential for the smooth running and organization of the project. Various tools are at our disposal in order to better organize ourselves and facilitate this communication within the group.

Internal communication also involves the development of meeting minutes with our supervisors as well as our client.

*Table 6 : Internal Communication Tools*

| TOOL | LOGO | Goal |
|---|---|---|
| **Blackboard** | | Communication and document sharing space for group work. The various information of the project are accessible on this support |
| **Whatsapp** | | Organize project progress meetings Give the different information (date, time, place) of the meeting |
| **Sharepoint** | | Collaborative space that works like a website. It allows you to store, share and organize work |

## 10.2. External communication media

Communication is a necessary means of conveying ideas and information. A communication plan is necessary to ensure the success of a project. Communication is essential if we want to carry out the project on a larger scale, solicit customers or obtain sources of funding (e.g., sponsor)

This communication will be addressed to the NTNU school and organizations likely to finance and support the project.

<u>A logo</u>

The logo is intended to give an identity to the project. So, we chose to put The Wind Turbine in the center of the logo and represent the sky around. The name "Moulin à vent" is French, and it designates the ancestor of wind turbines.


*Figure 13. The logo*

A brochure

The brochure will highlight the essential elements such as some key data of our project in a clear and airway. Its purpose is informative, and it should be pleasant to read. It will be important to highlight our contact details so that potential supporters can contact us quickly.

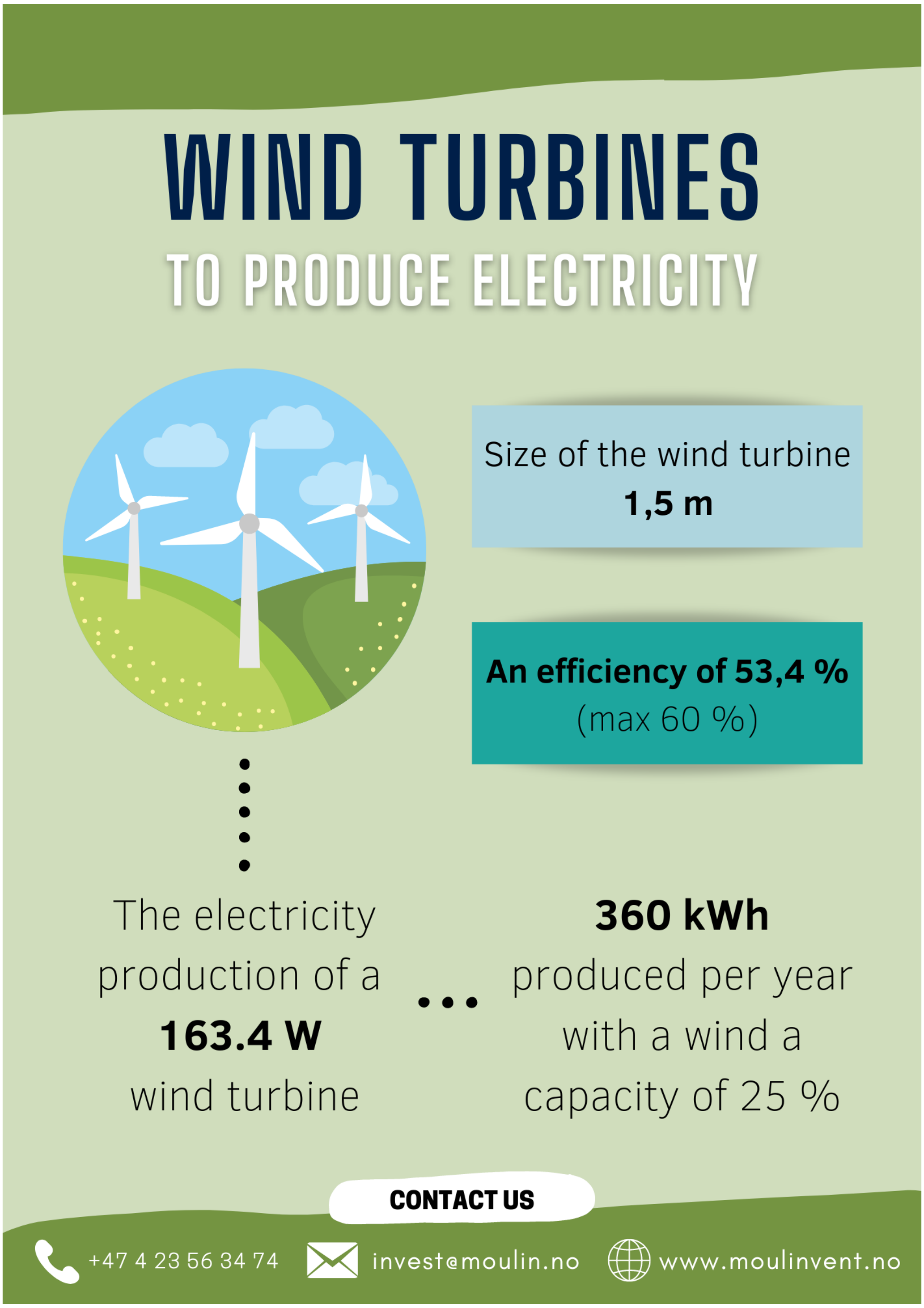



*Figure 14. Commercial brochure*

# 10. Final product

## 10.1. Introduction

The operating principle of a wind turbine is based on different mechanical and electromagnetic principles that will be explained later.

A wind turbine is a machine that will transform the kinetic energy of the wind into mechanical energy of the wind type and then be transformed into electrical energy and then be reinjected into the grid.

Under the effect of the wind, the rotor will start, and the blades will turn. A minimum wind speed of about 15 km/h is required. For safety reasons, the wind turbine automatically stops working when the wind exceeds 90 km/h.

The rotor then drives an axis of the nacelle, called a shaft, connected to an alternator. Thanks to the energy provided by the rotation of the axis, the alternator produces an alternating electric current.

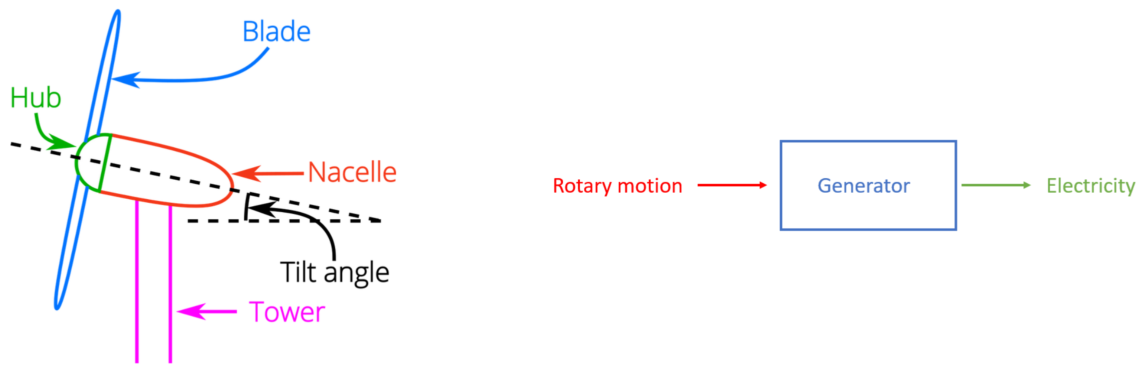



*Figure 15 : Diagram of a wind turbine and its energy conversion*

In our case, we will focus on the Horizontal Axis Wind Turbine (HAWT). The study focuses on a two-blade wind turbine which is an uncommon model on the wind n market which is generally 3 blades. The torque on the hub and tower is a little more balanced than the wind turbine a blade because the wind on the lower wing will compensate for the wind on the upper wing, and each time one wing goes up, the other goes down, which reduces the influence of gravitational acceleration.

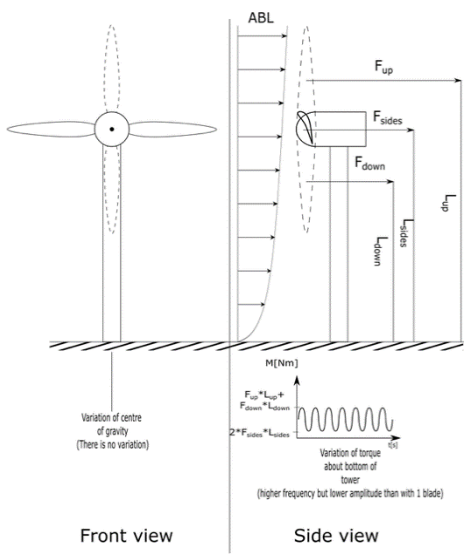



*Figure 16. Description and frequency of a two-blade wind turbine*

In order to obtain the optimal blade shape, the Blade Element Momentum (BEM) method will be used.

### 10.2. Flow around airfoil

If we section an airplane wing or wind turbine blade, we will get a characteristic shape, called an airfoil. Several parameters are important such as the chord length which is the reference length describing an airfoil, the angle of Attack which is given by the angle between the velocity on the blade and the line of the Chord Length.

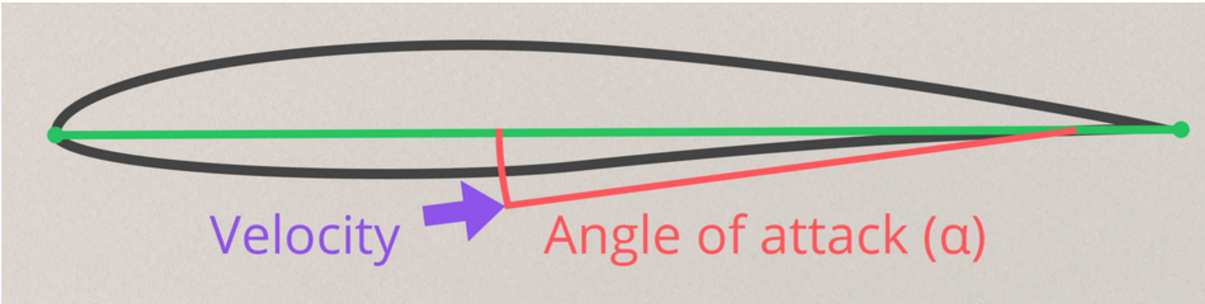



*Figure 17 : Airfoil Nomenclature*

An important concept of aerodynamics for a wind turbine to consider is the lift which is the driving force for wind turbine and another force plays an important role is the force call drag. The idea is to get the weakest drag to save energy and get better performance.

The origin of the lift can be explained using two principles: Bernoulli's principle and the Coanda effect. The Coanda effect is the tendency of a fluid to remain attached to a curved surface like water running down the back of a small spoon. Bernoulli's principle relates flow velocity and pressure and applies to permanent flows.

The most important concepts to remember are:

1) The airfoil deflects the air flow.
2) The air hence slows down and is deflected downwards (Coanda effect).
3) Based on Newton's third law, opposite forces are produced on the airfoil, hence lift and drag, respectively perpendicular and parallel to the flow.

Lift and drag [N] are defined as follows:

$$Lift = \frac{1}{2} \times \rho \times v^2 \times S \times C_L$$

$$Drag = \frac{1}{2} \times \rho \times v^2 \times S \times C_D$$

$$\rho = Fluid\ Density\ [\frac{kg}{m^3}]$$

$$v^2 = Flow\ velocity\ [\frac{m}{s}]$$

$$S = Reference\ area\ [m^2]$$

$$C_L = Lift\ coefficient\ [\emptyset]$$

$$C_D = Drag\ coefficient\ [\emptyset]$$

$C_L$ $and$ $C_D$ depends on airfoil geometry, angle of attack and Reynold number. If the angle of attack is too high, there is a risk of stalling. The flow is no more on suction side and separate from the leading edge. In addition, increases $C_L$ linearly as the angle of attack increases causes this stall. There will be immediate repercussions with a loss of lift and an increase in the drag. The aim is therefore not to reach this stage and therefore to monitor these parameters well during modelling and model analysis.

The Reynold number (Re) is a dimensionless number that determines whether the flow is laminar (weak Re) or turbulent (high Re). If the Re-number is high, the flow will be more energetic, and it is interesting with a significant angle of attack (AoA) because the stall will be done later but it will increase the drag. The larger the Reynold number and the higher the lift coefficient so there will also be a higher angle of attack and this will directly impact the lift equation. The same principle applies to drag. The Reynold number can be defined with the following relation:

$$Re = \frac{\rho \times v \times L_c}{\mu}$$

$$\rho = Fluid\ Density\ [\frac{kg}{m^3}]$$

$$v = Flow\ velocity\ [\frac{m}{s}]$$

$$L_c = Chrod\ Length\ [m]$$

$$v = Dynamic\ viscosity\ [kg/m.s]$$

### 10.3. Design and performance of a wind turbine

Today the realistic efficiency reached by a wind turbine is around 45% and the absolute highest efficiency is determined by the Betz limit.

A parameter that will allow to have an indication on the performance of the wind turbine and that it is important to calculate is the axial induction factor "a" which quantifies the relationship between wind speed and the speed at the wind turbine. The value of “a” giving the best efficiency is:

$$a = \frac{1}{3}$$

which means that the velocity of the wind turbine is the wind $\frac{2}{3}$ speed.

It is also possible to determine the power coefficient of the wind turbine which corresponds to the power actually extracted on the available potential power. The highest power coefficient is 60%, which corresponds to the Betz limit.

$$C_p = \frac{P}{P_{tot}}$$

If we plot the values of Cp for values of a between 0 and 1, so from no reduction in the wind speed from up streams, to full stop at the actuator disk, we can see that the power coefficient has a peak around a=0.333

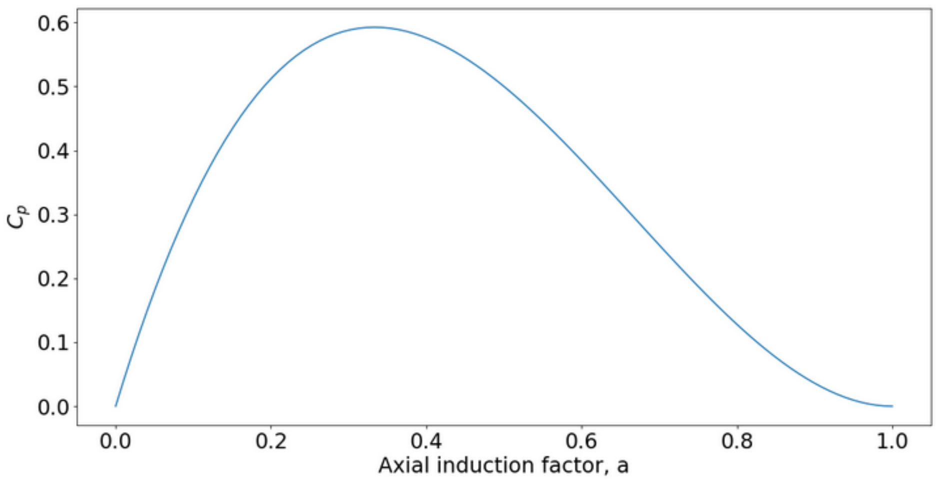



*Figure 18 : Representation of the Betz limit*

A last parameter that will influence the yield is the TSR (Tip Speed Ratio) which corresponds to the local ratio of the top speed. The formula is written as follows:

$$\lambda = \frac{\omega \times R}{V_i}$$

It describes the ratio between the blade velocity of a wind turbine, to the velocity of the incoming wind,$\omega \times RV_i$ . Efficiency increases with increasing TSR ($\lambda$).

For the entire project, we use Blade Element Momentum (BEM) to design an optimized blade for maximum power output. We will follow all the next step to get through it :

Design conditions :

1) Incoming parameters
    - Incoming wind speed V
    - Radius of the Blade
    - Rotational speed of the blade $\omega$
2) Found TSR
3) Choose an airfoil
    - Know the Lift (L)
    - Know the Drag (D)
    - Optimal angle of attack on the Blade
    - Number of Blade
4) Find the optimum values of " a " and " a' " for each blade element found at the average radius of element
5) Find the flow angle($\phi$) and the twiste angle ($\theta$) for each element
6) Find the thrust coefficient of the element and the chord length.

### 10.4. Electromagnetism around the generator

The generator is the element of a wind turbine that transforms mechanical energy into electrical energy. Once the current is produced, it is usually injected into the power grid.

The generator is a rotating machine composed of a stator (Has winding(s) with AC power) and a rotor (Different topologies: PMSM od Wound-rotor SM) as well as a gearbox to multiply the speed of rotation.

In our case study we will focus on the analysis, design and design of a permanent magnet synchronous machine (PMSM).

In the case of synchronous machines, the rotor must rotate at a constant speed dependent on a certain frequency (at the so-called synchronous speed). This frequency is generally imposed by the network (50H) and the rotor of the generator therefore rotates at a fixed speed imposed by the network that cannot be changed.

A magnetic field is generated at the rotor using a permanent alike or an electromagnet supplied with direct current.  The specificity of synchronous machi is that the rotor rotates at the same speed as the voltage frequency applied to the stator divided by the number of pole pairs of the machine:

$$n = n \times s = \frac{f}{p}$$

$$n = Vitesse\ de\ rotation\ du\ rotor$$

$$ns = Vitesse\ de\ synchronisme$$

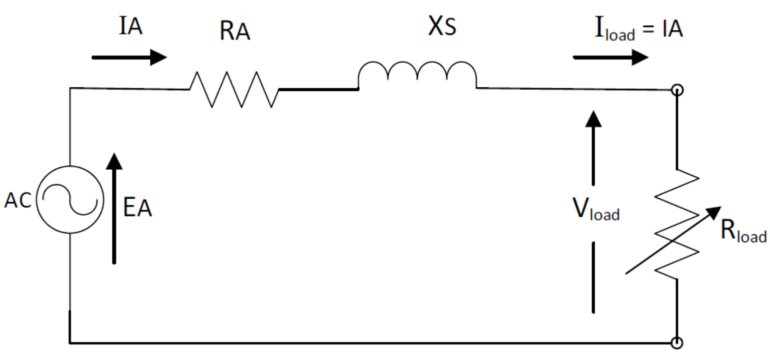
$$f = fréquence\ de\ la\ tension\ au\ stator$$

$$p = nombre\ de\ paires\ de\ pôles$$

Four basic principles explain how magnetic fields influence the space around them:

1) A current-carrying wire produces a magnetic field in the area around it
2) A time-changing magnetic field induces a voltage in a coil of wire if it passes through that coil. (This is the basis for transformer action.)
3) A moving wire in the presence of a magnetic field has a voltage induced in it (This is the basis of generator action.)
4) A current-carrying wire in the presence of a magnetic field has a force induced on it. (This is the basis of motor action.)

These four notions are important to understand in order to know how the generator that will be designed and built will work and behave.  Today magnetic formulas can be approximated by electrical formulas which makes it possible to obtain the following equivalent electrical diagram for PMSM:




$$\vec{E}_A = \vec{V}_\phi + R_A \cdot \vec{I}_A + j \cdot X_S \cdot \vec{I}_A \quad [V]$$

*Figure 19 : Per phase representation*

This will allow us after applying the law of Kirchhoff knots to calculate the induce voltage that will take us:

$$E_{A_{peak}} = \frac{8}{P}\pi \cdot f_e \cdot N \cdot B_p \cdot l_r \cdot r_r \cdot k_W$$

$P$ – *Number of* ***Poles***

$N$ – *Number of turns*

$f_e$ – ***Electrical*** *frequency (remember)* $f_e = f_m \frac{P}{2}$

$l_r$ – *Rotor lengthRotor radiusWinding factor*

$r_r$ – *Rotor length*

$k_W$ – *Winding factor*

$B_p$ – ***Peak magnetic flux density***

Some parameters are imposed by the customer as kw which must be between 0 and 1, the number of poles (limited between 2 and 4).

We can then calculate the efficiency which depends on the speed of rotation as follows:

$$\eta = \frac{P_{load}}{P_i + P_{loss}}$$

Other parameters will then be calculated using an excel that will centralize all equations and parameters for the analysis and design of the prototype. In order to better analyze our prototype, we will also produce a generator power curve which will correspond to the combination between the turbine power curve and the generator power curve. The idea is to vary the load resistance and the different input parameters of the excel so that we find ourselves in the case of a balance energy which will mean a stable equation. We must be vigilant because changing the load resistance will impact the rotational speed of the blade.

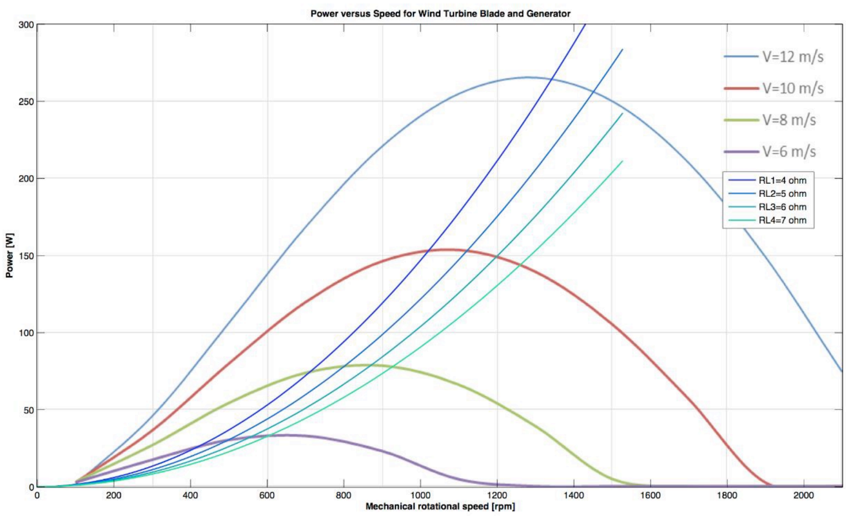



*Figure 20 : Power versus speed wind turbine blade and generator*

Finally, once all this phase of calculation, analysis and design of the rotor is done, the prototype can be produced.

# 11. Design et Analysis of the Blade and the Generator

To simulate and obtain the results of our wind turbine, we will use the ASHES software. It is a design and analysis tool for the simulation of onshore and offshore wind turbines. It is therefore necessary to familiarize yourself with the software. For this we selected a wind turbine e blade and made several tests on it by changing parameters. This allowed us to see what result we achieved and how to modify the different elements of the blade.

In a second step we made the preliminary design of the blades. It is carried out using the theory of angular momentum of blade elements (BEM). The goal is to find the most optimal blade geometry. For this we coded an algorithm in python language by estimating several initial parameters (Reynold number, chord length, air parameters, axial and angular induction factors)

The algorithm will allow us to obtain the values of the chord and twist angle for each element of the blade.

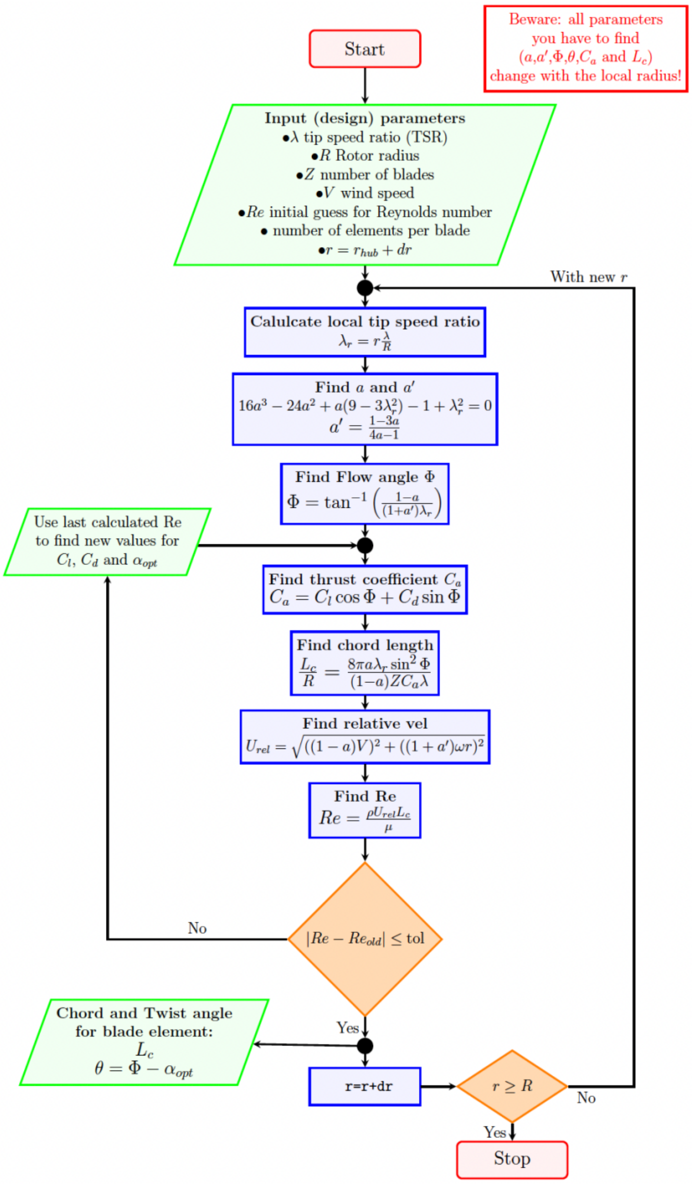



*Figure 21. Logical flow diagram with parameters and procedure for implementing BEM*

| r/R | $L_c$/R | Θ [deg] | a | a' | $\alpha_{opt\ [deg]}$ |
|---|---|---|---|---|---|
| 0,067 | 0,245 | 36,401 | 0,298 | 0,543 | 5,889 |
| 0,133 | 0,260 | 24,421 | 0,317 | 0,183 | 5,579 |
| 0,200 | 0,225 | 17,046 | 0,324 | 0,089 | 5,414 |
| 0,267 | 0,188 | 12,313 | 0,328 | 0,052 | 5,397 |
| 0,333 | 0,160 | 9,198 | 0,330 | 0,034 | 5,336 |
| 0,400 | 0,138 | 6,993 | 0,331 | 0,024 | 5,297 |
| 0,467 | 0,121 | 5,357 | 0,331 | 0,018 | 5,273 |
| 0,533 | 0,107 | 4,099 | 0,332 | 0,014 | 5,258 |
| 0,600 | 0,096 | 3,104 | 0,332 | 0,011 | 5,248 |
| 0,667 | 0,087 | 2,299 | 0,332 | 0,009 | 5,241 |
| 0,733 | 0,080 | 1,633 | 0,333 | 0,007 | 5,236 |
| 0,800 | 0,073 | 1,075 | 0,333 | 0,006 | 5,233 |
| 0,867 | 0,068 | 0,601 | 0,333 | 0,005 | 5,230 |
| 0,933 | 0,063 | 0,192 | 0,333 | 0,005 | 5,228 |
| 1,000 | 0,059 | -0,163 | 0,333 | 0,004 | 5,226 |

*Figure 22. Results of rope and twist angle dimensions for each blade element*

Once the preliminary geometry of the blade is established, it is possible to calculate the total power produced, the power coefficient and the thrust coefficient.

- Power = 358.8 W
- Power coefficient = 0.544
- Thrust coefficient = 0.927

Now that we have obtained the preliminary design of the blade, we will get the actual design to be able to implement it on ASHES. Thus, we will be able to study the performance of the rotor and those of the loads acting on the blades.

The preliminary design must respect certain limits, so as not to break during 3D printing of the blade. The machine imposes a maximum of 900X98X48mm. To ensure that the blade is suitable for the printer we have checked that:

$$L_c \,.\cos\theta \ < \lim_x$$

$$L_c \,.\sin\theta \ < \lim_y$$

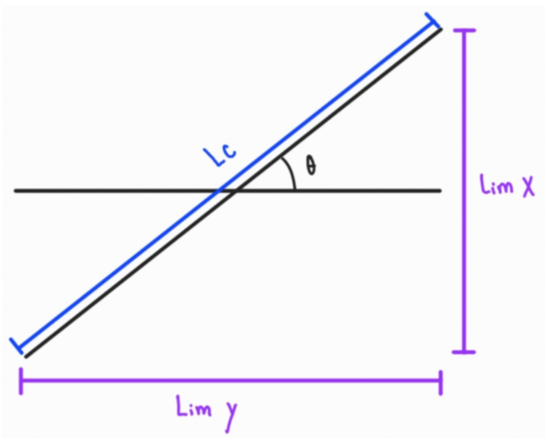



*Figure 23. Estimation of limit values in x and y*

For the rest we fixed the size of the rotor and hub.

$$D_{rot} = 0{,}9\ m$$
$$D_{hub} = 0{,}06\ m$$

| NACA2414 | | | | | |
|---|---|---|---|---|---|
| Section | r [m] | $r - r_{hub}$ [m] | $L_c$ [degree] | $\vartheta_{opt}$ [degree] | Fit |
| Circle | 0,03 | 0,00 | 0,048 | 0 | TRUE |
| 1 | 0,06 | 0,03 | 0,101488 | 28,22679 | FALSE |
| 2 | 0,09 | 0,06 | 0,104651 | 20,53705 | FALSE |
| 3 | 0,12 | 0,09 | 0,101619 | 15,33692 | FALSE |
| 4 | 0,15 | 0,12 | 0,100107 | 11,77501 | FALSE |
| 5 | 0,18 | 0,15 | 0,088517 | 9,191631 | TRUE |
| 6 | 0,21 | 0,18 | 0,078324 | 7,243536 | TRUE |
| 7 | 0,24 | 0,21 | 0,070007 | 5,729149 | TRUE |
| 8 | 0,27 | 0,24 | 0,063161 | 4,521879 | TRUE |
| 9 | 0,30 | 0,27 | 0,057462 | 3,538880 | TRUE |
| 10 | 0,33 | 0,30 | 0,052662 | 2,724059 | TRUE |
| 11 | 0,36 | 0,33 | 0,048574 | 2,038289 | TRUE |
| 12 | 0,39 | 0,36 | 0,045056 | 1,453542 | TRUE |
| 13 | 0,42 | 0,39 | 0,042001 | 0,949265 | TRUE |
| 14 | 0,45 | 0,42 | 0,040324 | 0,510072 | TRUE |

*Figure 24. Blade Design Parameters for the CNC-Machine*

In the figure above we can see that it is necessary to change the parameters to yellow, because they are too large to be printed with the machine, so we have decreased them. This does not matter because the effect on aerodynamics will be very small.

Now we will study the blade obtained on ASHES. We get a power coefficient of 44% while the BEM code gave us a coefficient of 5.4%.

The difference between these two values can be explained by different factors such as:

- The existence of the rotor hub.
- The loss at the tip of the blade.
- Loss in a turbulent fluid (in the BEM model, the fluid is assumed to be perfect).
- Boundary layer on the ground, in front of the fin.
- Presence of the tower supporting the turbine.

We also compared the results obtained between the BEM code and ASHES for the different angles of attack along the blade. The two angles do not correspond near the foot and at the tip of the blade, which can be explained by the decrease in size at the tip of the blade and the presence of the hub. These two elements disturb the flow and therefore the angle of attack.

Now we will design an Excel sheet that will be used to size the generator. The Excel was given to us by our teachers, and we had to fill in the empty cells with the right equations.

Below will be presented the different input parameters that we will use throughout the excel. First of all, there are the input parameters, among which we find the number of poles, phases, the diameter of the copper cable and the number of windings that can be varied to obtain the best possible result.

| USER INPUT | Symbol | Value | Unit | Typical values | Comments |
|---|---|---|---|---|---|
| **Dynamic properties** | | | | | |
| Rotational speed of rotor | RPM | 1500 | | 100-2000 | |
| Resistance of load per phase | Rload | 4 | *ohm* | 0.5-50 | *0 means short circuit, infinity means idling (tomgang)/broken curcuit* |
| **Geometry** | | | | | |
| Distance from axle to middle of conductor bundle | r | 0,055 | *m* | 0,055-0,065 | *Distance from center axle to middle of conductor bundle. Set by geometry* |
| Active length of coil | Lactive | 0,12 | *m* | 0,12 | *Restricted by test setup. Cannot be larger than 195mm. Current rotor design has a magnet length of 120mm* |
| **Rotor and flux** | | | | | |
| Number of poles | P | 2 | *[-]* | 2 or 4 | *The number of poles on the rotor. This is also the number of magnets* |
| Flux density (middle of coil in radial dir.) | B | 0,2 | *Tesla* | 0,1-0,25 | *Should be calculated analytically or taken from the graph in the lab manual* |
| **Stator (armature)** | | | | | |
| Number of phases | Nphase | 3 | *[-]* | 1 or 3 | *Up to the designer's discretion (1 = higher peak voltage but more ripple)* |
| Resistivity of copper at the reference temperature | rho0 | 1,68E-08 | *ohm*m* | 1,68*10^-8 | *Is a given constant* |
| Reference temperature of copper | T0 copper | 20 | *C* | 20 | *Is a given constant* |
| Temperature of copper under test | T copper | 30 | *C* | 20-60 | *Should be roughly estimated* |
| Thermal coefficient of the resistivity of copper | k_temp | 6,79E-11 | *ohm*m/C* | 0,00404 | *Is a given constant* |
| Diameter of the copper wire | D_copper | 0,001 | *[m]* | 0,5-2 | *Diameter of the copper. 2 options will be made available in the lab manual* |
| | Rcorr | 1,15 | | 1,15 | *Takes into account the extra resistance in the connectors* |
| Number of turns per. coil | Nturn | 50 | *[-]* | 20-60 | *Higher number of turns gives higher induced voltage, but also higher winding resistance* |
| Length factor | Lcorr | 1,05 | | 1,05 | *Takes into account the extra length in the bends. 1,05 is a good reference value.* |
| Winding factor | fw | 0,9 | *[-]* | 0.8 - 0.99 | *0.9 is a good (conservative) estimation. When using the matlab tool, the fundamental winding parameter can be taken from there* |
| Number of coils in series (i.e. per phase) | Ns | 2 | *[-]* | 1/2/4 | *Depends on the winding layout chosen.* |
| **Misc.** | | | | | |
| Ref. number of turns per coil | N0 | 28 | *[-]* | 28 for radial | |
| Ref. stator coils inductance pr phase (SINGLE-PHASE) | Ls0 | 0,0008 | *H* | | *Reference value for 28 turns SINGLE-PHASE and specified coil shape* |
| Ref. stator coils inductance pr phase (THREE-PHASE) | Ls0 | 0,0008 | *H* | | *Reference value for 28 turns THREE-PHASE and specified coil shape* |
| Ref rpm for loss | omega0 | 1000 | *RPM* | | *Rotational speed used to calculate the reference value Ls0* |
| Ref friction and ventilation loss | Floss ref | 20 | *W* | 10-30 | *Assumed to be linearly dependent on speed* |

In the first part, we found an expression for the voltage induced in the coil.

| | | | | |
|---|---|---|---|---|
| Rotational speed | **omega** | 157,08 | ***rad/s*** | (1) |
| Linear speed | **v** | 8,6 | ***m/s*** | (2) |
| Peak induced voltage in a single loop | **e** | 0,4 | ***V*** | (3) |
| Peak induced voltage in a coil | **E_a** | 26,4 | ***V*** | (4) |

*Figure 25. Induced voltage Results*

$\omega = RPM \,. \frac{2\pi}{60}$ (1)

$v = \omega \,. r$ (2)

$e = (v \,. B).\, l_{total}$ (3)

$E_a = \frac{e}{\sqrt{2}} \,. f_w .\, N_s .\, N_{turns}$ (4)

Then the stator resistance per phase.

| | | | | |
|---|---|---|---|---|
| Wire length per turn | **Lturn** | 0,615 | ***m*** | (1) |
| Total length of wire in stator | **Lstator** | 123,0 | ***m*** | (2) |
| Copper wire cross-sectional area | **Acs** | 7,85E-07 | ***m^2*** | (3) |
| Stator resistance per meter | **Rcopper** | 0,022 | ***Ohm/m*** | (4) |
| Stator resistance per phase | **Rtot** | 3,15 | ***Ohm*** | (5) |

*Figure 26. Stator results*

$$L_{turn} = 2 \, . \left( \frac{2\pi r}{N_{poles}} + l_{active} \right) . \, l_{corr} \quad (1)$$

$$L_{stator} = N_s \, . \, N_{turn} \, . \, N_{poles} \, . \, N_{phases} \quad (2)$$

$$A_{cs} = \frac{\pi}{4} \, . \, D_{copper}^2 \quad (3)$$

$$R_{copper} = \frac{1}{A_{cs}} \, . \, (\varrho_0 + (T_{copper} - T_{0copper}) . \, k_{temp}) \quad (4)$$

$$R_{total} = \frac{R_{copper} \, . L_{stator} \, . R_{corr}}{N_{phases}} \quad (5)$$

**Problem 1. Reactance and current:**

Phase inductance is given by: $L_s = L_0 . (\frac{N}{N_0})^2 \, . \, N_s$

Electrical frequency is given by: $\omega_e = \omega \, . \frac{P}{2}$

Stator coil reactance per phase is given by: $X_s = L_s \, . \, \omega_e$

Current per phase is given by: $I = \frac{E_a}{\sqrt{(R_{tot} + R_{load})^2 + X_s{}^2}}$

Terminal Voltage is given by: $V_{term,ph} = R_{load} \, . \, I$

| | | | |
|---|---|---|---|
| Stator coil inductance per phase | Ls | 0,00574 | H |
| Electrical angular velocity | omega_e | 157,1 | rad/s |
| Stator coil reactance per phase | Xs | 0,90 | ohm |
| Current per phase | abs(I) | 6,7 | amp |
| Phase voltage | Vterm,ph | 27,0 | Volt |

*Figure 27. Reactance and current results*

**Problem 2. Power:**

Power delivered to the resistor is given by: $P_{load} = R_{load} \, . \, I^2$

Power losses in copper wire are given by: $P_{loss} = R_{tot} \, . \, I^2$

Friction and ventilation loss are given by: $F_{loss} = 10 + 30 \, . \frac{RPM}{RPM_0}$

Total mechanical power is given by: $P_{in} = P_{load} + P_{loss} + F_{loss}$

Efficiency is given by: $\eta = \frac{P_{load}}{P_{in}}$

| | | | |
|---|---|---|---|
| Power (electrical) | Pload | 546,4 | Watt |
| Power loss (copper wire losses) | Ploss | 63,8 | Watt |
| Friction and ventilation loss | Floss | 40,00 | W |
| Power (mechanical, from wind) | Pin | 650,1 | Watt |
| Efficiency | eta | 84,0 % | |

*Figure 28. Power Results*

The objective now is to design a generator with the best possible efficiency at the design point of a wind turbine model, given by the design regime and the torque produced by the rotor blades. At this point, the net torque on the shaft from the turbine and generator blades must be zero, so that the maximum wind energy is transferred as mechanical energy into the blade blades of the turbine and then as electrical energy into the generator at a constant rotational speed.

The results for generator sizing are as follows:

- 2 poles
- 3 phases
- 1.2 mm diameter for copper cable
- 56 windings

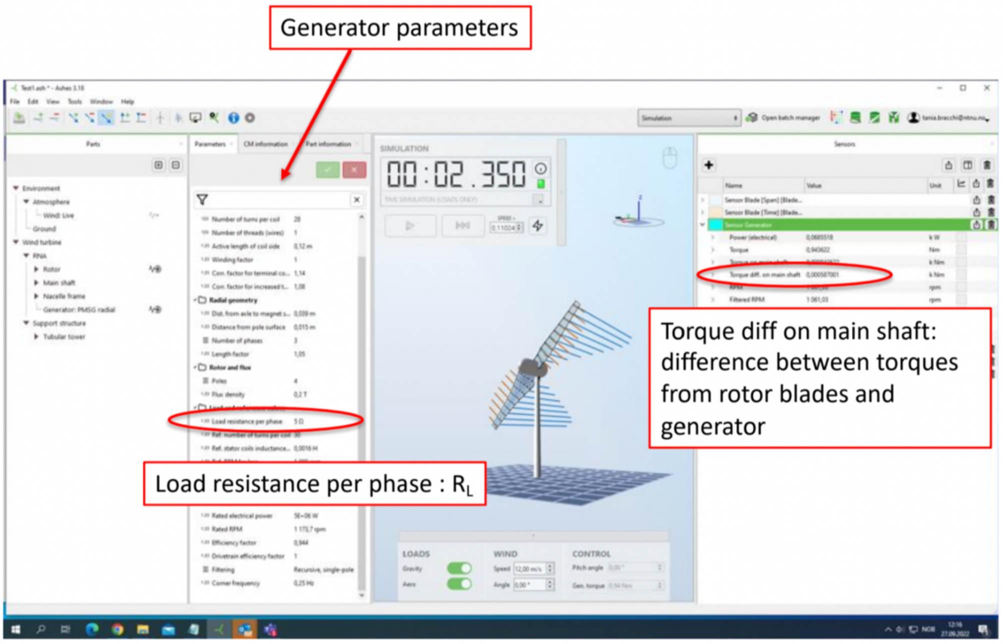



*Figure 29. ASHES generator Parameters*

# 12. Construction and testing of the wind turbine

## Construction of the generator

We started by building the generator. For this we cut 6 times 25 m of copper wire, then we created our coils. We created wooden supports to give shape to the coil, then wrapped the copper wire around itself to achieve 56 turns as advertised in the design settings. Finally, we get 6 coils that we have connected together so as to form a ring. So we have a rotor composed of 3 phases and 2 poles. All the connectors have been added to make the different connections for the test phase.

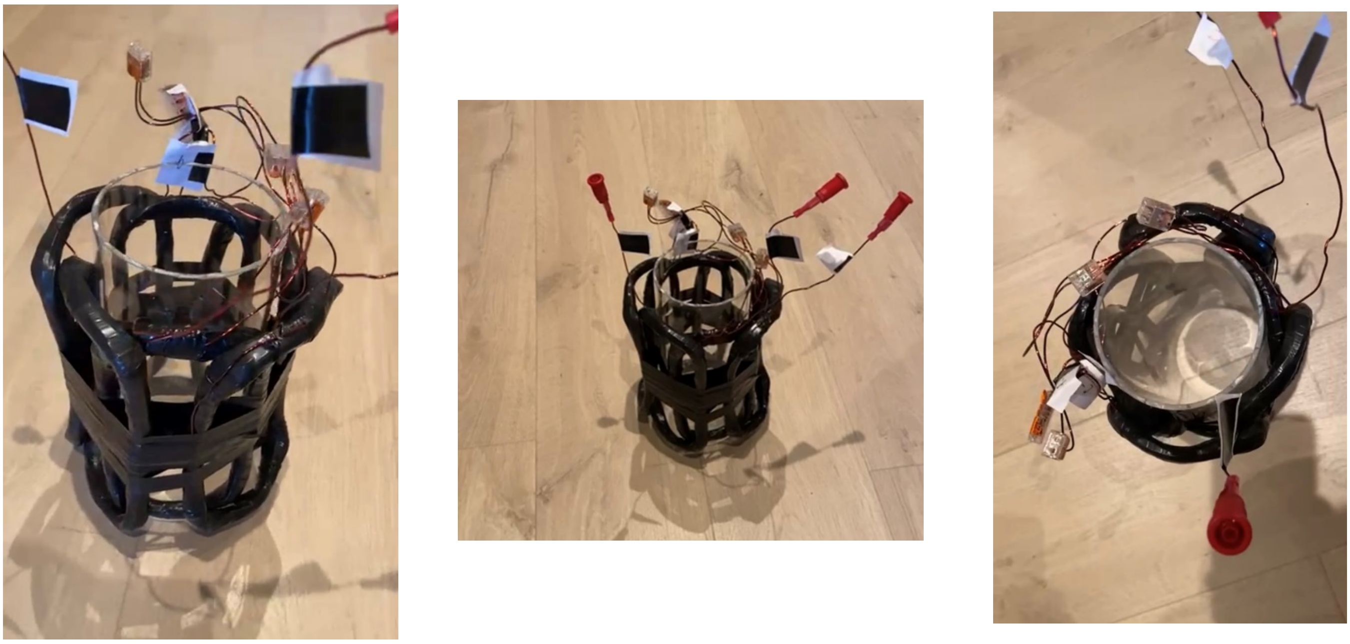


*Figure 30 : Generator*

## Construction of wind turbine blades

For the construction of the wind turbine blades, the printing was done using a 3D printer that was made available by the school. The blades were printed according to specific dimensions that were specified earlier in the report and in PLA material which is a non-toxic biodegradable plastic.

*Figure 31 : Wind Turbine Blade*

## Generator test phase

Once the generator was built, we focused on the testing phase. The latter was carried out in NTNU's laboratories on an experimental test bench like this one:

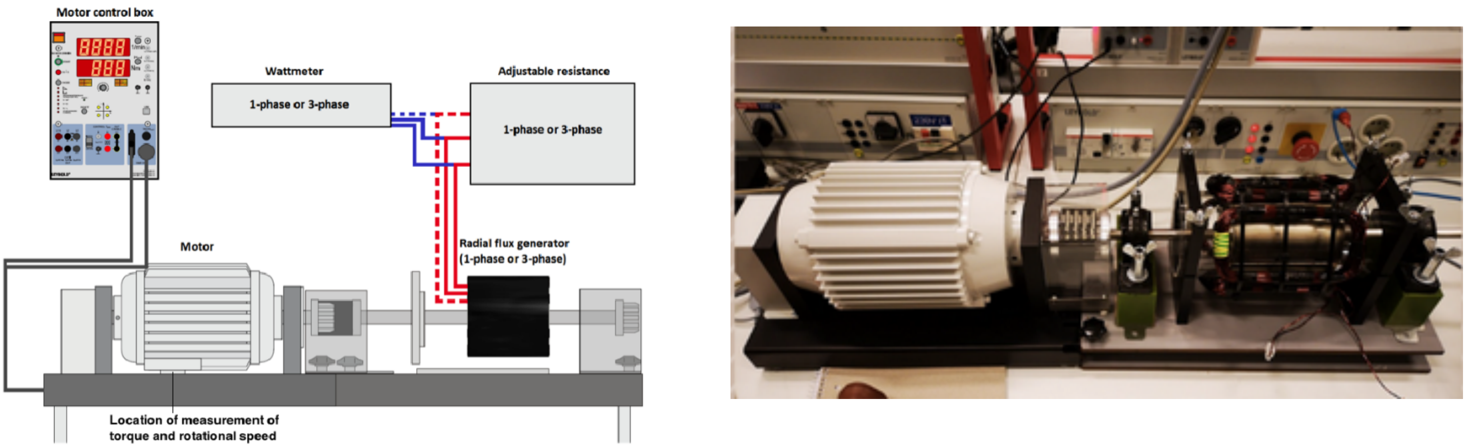



*Figure 32 : Test rig for the radial flux generator*

The idea of this test phase is to measure the different parameters, record them in order to be able to compare them with the estimated and simulated values. The driving force used will be that of an engine. We carried out this test phase and all the recorded parameters were faithful to what we were supposed to achieve. There is obviously a certain margin of error to be taken into account because we are not in a perfect environment and there is therefore a relative error. However, it remains sufficiently low and therefore negligible.

## Implementation of the final system

The last test phase is the one on the test bench in the wind corridor with the wind turbine blade and the rotor as below:

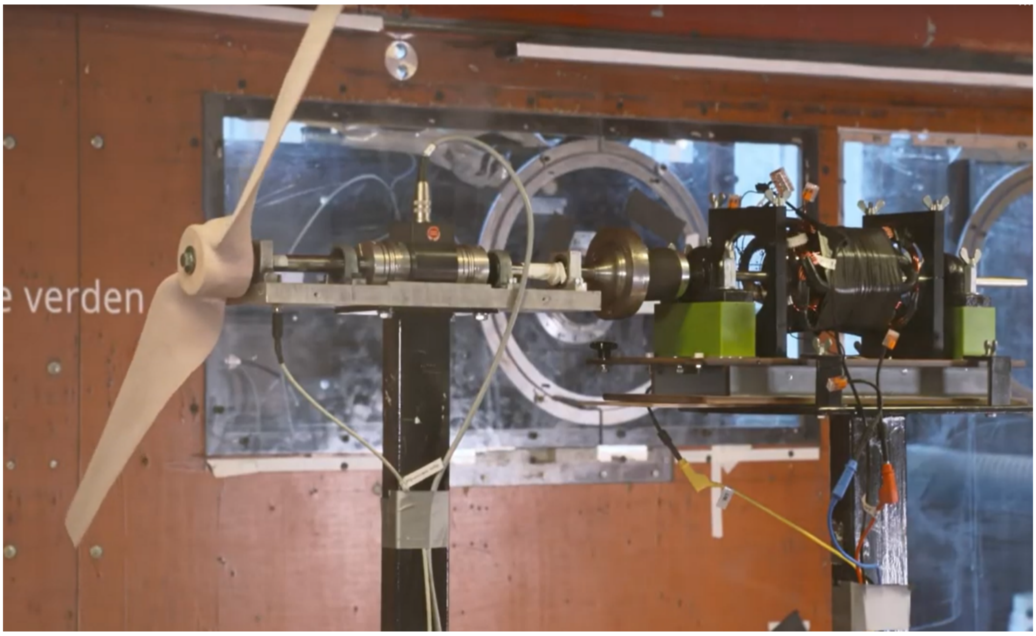



*Figure 33 : Test bench for the final wind turbine test*

This time the driving force will be that of the blades of the generator which will be actuated under the effect of the wind of the wind tunnel. The entire prototype is connected using connectors that allow the various information to be measured live. In particular, they are connected to a pressure transducer and a data logger. These are connected to a PC that will read and acquire the following data:

- Wind speed [m/s]
- Rotational speed [rpm]
- Current[A]
- Voltage [V]
- Total efficiency [%]

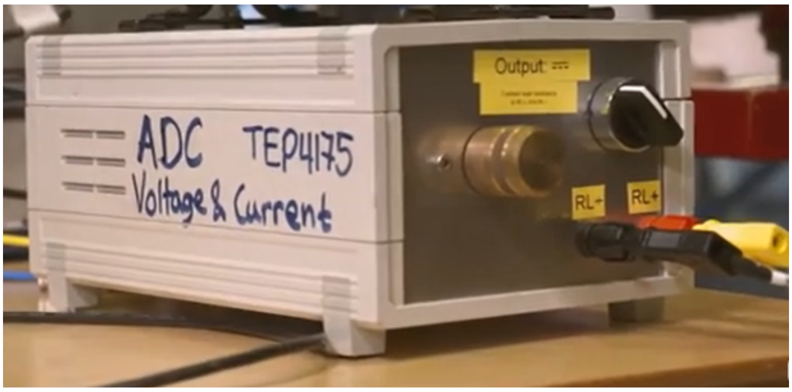



*Figure 34 : Data Logger Image*

After this phase of test, we obtained a final efficiency of 53.4% which is more than satisfactory considering that the maximum efficiency is 60%. It is rare to obtain a perfect efficiency of 60% given the margins of error, the rotor having been made by hand, 3D printing also has slight errors but the whole remains negligible.

Calculation of the relative error:

$$e = \frac{|60 - 53{,}4|}{53{,}4} = 12{,}3\%$$

The relative error being less than 15% we consider these results as very satisfactory.

In conclusion, we are very satisfied with both the prototype and the results obtained. Thanks to a thorough management and project management, we were able to complete this project on time, in accordance with the client's request and the expressed need.