Overall report Wp7 – HZ Part

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1 Project details

AIRTuB is a cooperation project between Stork AMT, ECN-TNO and several Dutch universities and companies. The consortium intends to prove in this project that more advanced automated sensor -and coating systems can enhance inspection and repair operations around offshore wind parks, in order to increase AEP and decrease the cost of O&M.

The figure below provides an overview of the different work packages of the project as defined at the start. Here WP 7 is discussed. This sub-project has been elaborated by the HZ Assetmanagement research group (A. Repko), TNO (V. V. Dighe) and Stork (L. Pijpker). This current document considers the HZ part. In WP7 an Asset management strategy is developed, based on the previous WP's and a prototype dashboard is developed based on the outcomes of WP6. The knowledge gained in this project will be disseminated in WP8.

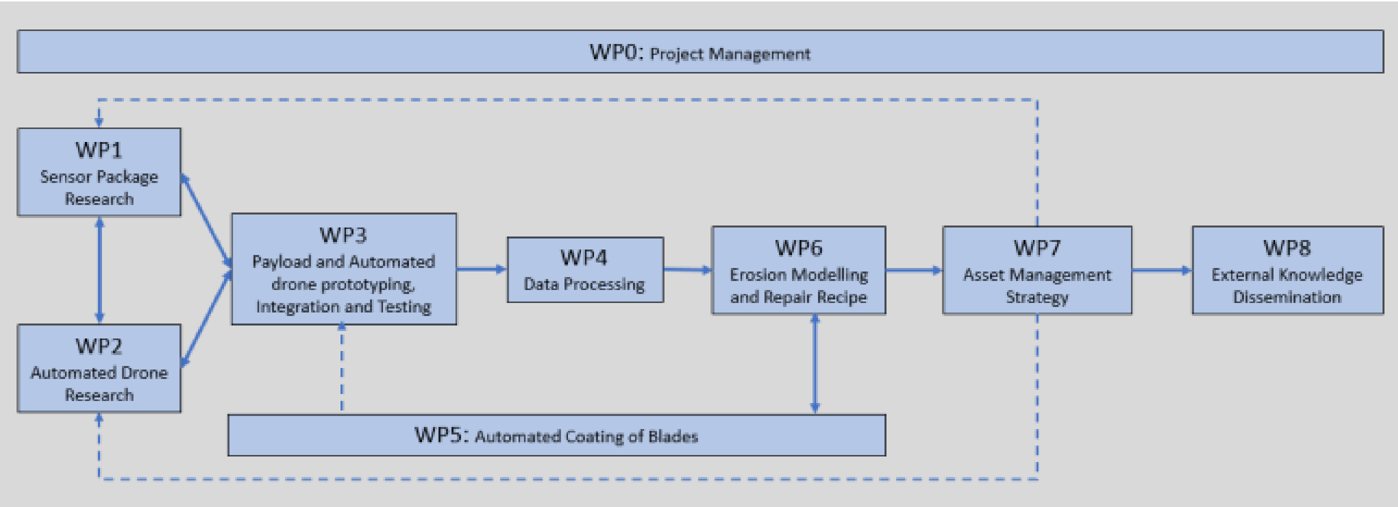


Fig. 1.1 Project WP configuration (Field Lab Zephyros (2019))

2 Final report on the contents of the project

Below is a summary report of the activities carried out by the HZ asset management research group within work package 7 of the Airtub project. This brief document is largely based on the report *Wp 7 Business case report* (HZ, TNO, Stork (2022)). The latter report is much more detailed and provides a more complete overview of the HZ workpackage 7 activities and research results.

2.1 Summary

Main research question of work package 7:
How do the benefits, costs and risks of inspection (and repair) methods with the AIRTuB drone compare to those of the current inspection methods of the Amalia wind park?

Initial scope of wp7
Comparing the following scenarios based on a business case:

- Baseline: Inspection and repair by rope access;
- Scenario 2: Inspection with AIRTuB drone, repair by rope access
- Scenario 3: Inspection with AIRTuB drone, repair with AIRTuB drone

The mentioned repair works are relatively simple repairs of minor damages that can be done manually via rope access or by the AIRTuB drone with the crawler mechanism.

The problem is that, at this moment it is not yet feasible to compare the above 3 scenarios completely and accurately, making adjustments necessary, see following update. Particularly the information and/ or data with respect to the actual damage (from the Amalia wind park), the existing repair techniques and those of the AIRTuB drone is too limited/ incomplete and not accurate enough for this. It also appears that the baseline is now too restrictive since drones with 4k cameras are already being used on a large scale in practice. Furthermore, as said, currently there are also some promising test results with relatively lightweight drones containing both the 4k camera and the laser line scanner unit which might be the best option as it seems to combine the best of both worlds (the light weight of the current drones, and the advantage of the inclusion of the laser line scanner). Finally nowadays in the work field more and more the use of a so-called HUB is considered, as an attempt to lower the maintenance costs by reducing the relatively high transportation/ vessel costs.

Updated scope of wp7
To consider the above, **the business case scenario comparison has been updated** and further refined as shown in the table below.

Table 2.1: Updates scenarios of business case comparison

	Airtube 1 - Excluding use of crawler for small repairs			Airtube 2 - Including use crawler for small repairs		Airtub 1 or 2 optional
	Baseline 1	Base Line 2	New Scenario 1	New Scenario 1b	New Scenario 2	New Scenario 3
Description	Visual Inspection via rope Access	Drone inspection with 4k Camera and repairs with rope access ([1])	Yearly inspection of all blades with (4k camera+) laserscanner but crawler only at the end of the lifetime for 1 or 2 critical points on the blade	Yearly inspection of all blades with (4k camera+) laserscanner. Crawler is used for small repairs (Cat 1 and 2) and utrasonic scanner of crawler only at het end of the lifetime for 1 or 2 critical points on the blade	Autonome inspection with (4k camera+) laser scanner and crawler having a HUB and also small repairs are done by crawler (cat 1 and 2)	Yearly inspection of all blades with (4k camera+) laserscanner on a small drone. Crawler with utrasonic scanner with large drone only used at the end of the lifetime for 1 or 2 critical points on the blade
Logistics	Small ship, more often to go for inspections than in case of drones	Small ship, less often to use because of higher efficiency of drone inspections	Large ship needed for big drone	Large ship needed for big drone	Large ship only needed for maintenance of drone, crawler and HUB and providing supplies	Small Ship for small drone, large ship for big drone
Difficulties	A lot of visits, time consuming checks, Weather conditions	Immages have often not a good focus, quality is limited, extra work at rope access for repairs. Weather conditions	Need operator for old fields to pitch blades into position	Need operator for old fields to pitch blades into position	Calculations HUB, still need operator for old fields to pitch blades into position	small drone is more sensitive for wether conditions,still need operator for old fields to pitch blades into position
Advantages		Less logistic costs	Less repair time because better insight LEE	Less reapir time and possible extension of lifetime due to good insight of internal health of the blade using utrasonic sensor	Less reapir time and possible extension of lifetime due to good insight of internal health of the blade using utrasonic sensor	Savings on logitic costs,
Extra options			Theoretical calculation of innitiating inspection not yearly but based on decreasing performance (using SCADA data)	Repairs are done	HUB and repairs	Combination of small drone and big drone, repairs

([1]) Only additional costs of minor repairs (4) due to inefficiencies due to lower quality of data inventory

Some clarification, specifically:

- new scenario 1b and 2 will be analyzed in detail in the next AIRTuB 2 project as in that part the automated <u>repair abilities</u> of the AIRTuB crawler will be developed;
- the so called '4k camera drone' is the 'average' relatively light-weight drone type that is <u>currently</u> used for the inspection works of the Amalia Wind park. It is launched from a CTV (Crew Transfer Vehicle) and only contains 1 inspection tool, the 4k camera;
- the new AIRTuB drone with crawler mechanism is bigger and heavier (*) and therefore needs to be transported with a SOV vessel ((*) at least still at this moment, but optimizing is still going on);
- Further additional remarks: see *Wp 7 Business case report.*

<u>Deliverables of business case comparison and HZ contribution</u>

- List business goals of using the developed automated blade inspection technology of the AIRTuB project;
- Develop and compare the three updated scenario's, including:
  - Benefits analysis
  - Cost analysis
  - Sensitivity/ Risk analysis
  - Validation with experts
- Provide overview of corresponding predictive maintenance performance indicators

Contribution HZ:

- HZ has contributed to all deliverables. For a detailed explanation see report *Wp 7 Business case report*
- The core of the works is the cost analysis incl. sensitivity analysis and vailidation. Only baseline 1,2 and New scenario 1 have been considered. The HZ made a global cost calculation of each, TNO a more extended and refined cost calculation using the TNO O&M Planner simulation tool.

Summary of Results/ conclusions/ discussion

See table below.

Table 2.2. Main results of cost comparison

	Vessel costs [k€]	Technician costs [k€]	Duration [days]
Baseline 1 [Calculation]	240	216	15
Baseline 1 [Simulation]	264	237,60	19
Baseline 2 [Calculation]	48	22,50	6
Baseline 2 [Simulation]	61,33	28,75	9
New Scenario 1 [Calculation]	72	27	6
New Scenario 1 [Simulation]	88	33	9

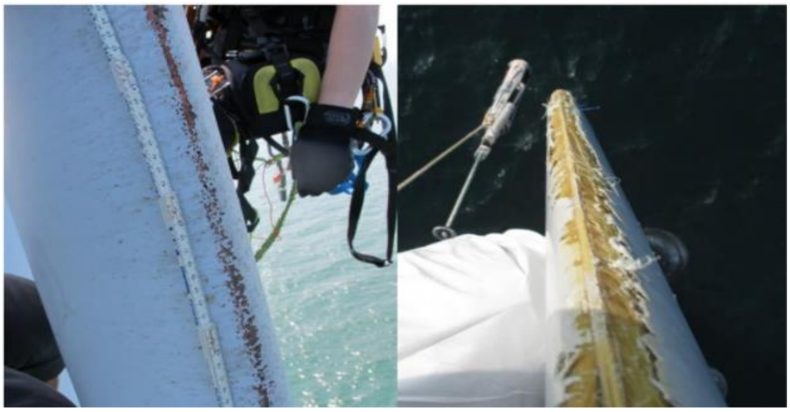
Further analysis, discussions, conclusions and recommendations: see following par 2.4.

2.2 Introduction

Background

The wind energy industry is a relatively young industry that has been operating for about 10-15 years. Many things are therefore still under development, including the O&M activities. This applies in particular to the relatively complex maintenance of the rotor blades. With components such as the gearbox and the turbine, the condition is already continuously monitored with a multitude of sensors, while determining the condition and damage patterns of the rotor blades remains a challenge.

This also applies to the assessment of Leading-Edge Erosion (LEE), a well-known damage of wind turbine blades induced by offshore weather conditions (water, salt, dirt) and damage from precipitation (rain, hail), see the image below.



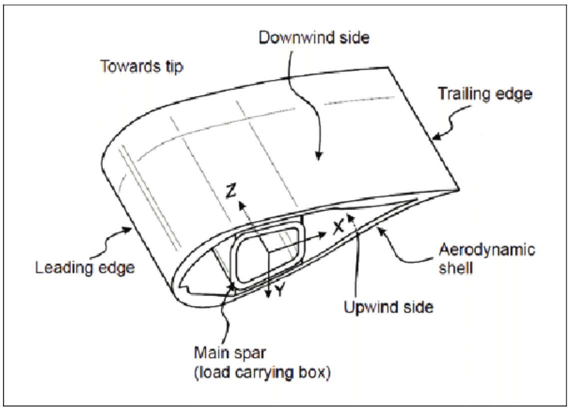


Figure 1.1: Left: Two examples of Leading-Edge Erosion (LEE) on operational offshore wind turbine blades. (P. Dvorak, 2016) Right: 3D visualization of blade section and the leading edge (LE).

AIRTuB is a cooperation project between Stork AMT, ECN-TNO and several Dutch universities and companies. The consortium intends to prove in this project that more advanced automated sensor -and coating systems can enhance inspection and repair operations around offshore wind parks, in order to increase AEP and decrease the cost of O&M.

The basic idea is:
- To use a drone platform with a sensor module for remote sensing to detect and measure the level of LEE of operational turbine blades. The drone with the module as load is launched from a SOV vessel (, a larger vessel that the CTV (Crew Transport Vessel), needed due to the relatively large size of the AIRTuB drone,) near an offshore wind turbine. The drone will hoover in front of the turbine blades to enable remote sensing and will land on the flat part of the blade in horizontal position where it will lock itself to the blade and crawl along its length.
- The first sensor package is aimed at detecting lE in an accurate 3D image format such that LEE can be followed during the life time. This package will do its measurements while hovering along the LE
- A second sensor package, to detect and measure structural damage, and third package, an automated coating system for the repair of LEE, will be developed in parallel. Both packages have the potential to be developed to plug and play modules in a later stage, that can be carried as payload by the drone. Both modules would require the drone to contact the blade, plus a crawler to be able to travel to the region of interest (blade in horizontal position during landing and crawling.

<u>Initial scope of wp 7, update, and HZ contribution</u>
See previous summary with required and updated deliverables..

<u>Problem statement</u>
Rope access and drone inspections are currently performed in the offshore wind farm industry and relatively simple repairs are also performed manually via rope access. In the AIRTuB project, a new drone is being developed with (, compared to those of the currently used drones,) advanced inspection techniques. In addition, the aim is to have this drone also perform the aforementioned simple repairs. At the moment it is not yet clear what the exact advantages of the application of this drone are from a cost perspective. It should also become clear what the possible additional benefits are in terms of risk, health and safety.

2.3 Objective/ goal

The ultimate goal from a broad perspective is clearly optimizing the asset management of the rotor blades to ensure that the wind turbines produce as much energy as possible during their complete service life time, based on an optimal balance between costs, risks and performance. This means limiting (unnecessary) downtime as much as possible and at the same time ensuring an optimal condition of the rotor blades with a risk based and data driven approach so that the above is achieved. Moreover, working on this accelerates the development of large-scale offshore wind energy, making it a competitive and sustainable energy source from an ecological and economic point of view.

Besides the focus of the AIRTUB project to reduce the Levelized Cost of Energy (LCoE) by means of optimizing the maintenance of the turbine blades, in addition it aims at reducing the need for people to be physically deployed to the offshore wind farm, hence reducing the risks of injury and facilitating remote maintenance of the rotor blades (health and safety). (Current practice also shows that the availability of persons to be willing to do rope access work is limited.) Furthermore, the aim is also to reduce the environmental impact of the O&M works.

Business goals

More specifically from a business point of view and related to the actual content of the AIRTuB project the main purpose is to prove that more advanced automated sensor- and -coating systems will be able to have a significant contribution in this. These systems will optimize the inspection and repair operations around offshore wind parks. This by means of higher quality inspections providing much more extensive and more accurate information about the condition of the turbine's blades, but also done in a shorter period of time. Better data will help improve the overall quality and effectiveness of the maintenance

In order to translate the above rather globally described main business goal into SMARTER formulated and detailed ones, the other work packages must first be further elaborated so that it is clear what is actually feasible with the new techniques. Based on this realistic performance requirements can be defined. By both following a top-down and bottom-up approach, the actual detailed business goals can be more sharply defined. Probably it is best to finalize this in the following AIRTuB 2 project when also the automated repair tools of the AIRTuB have been developed and tested.

Document Project Plan Hernieuwbare Energie 2019 (Field Lab Zephyros (2019)) indicates what might be possible in future: "By using autonomous drones for inspection, for both LEE and structural damage inspection, as well as for leading edge maintenance, 80% of the manual work for inspections may be performed much more efficiently and safely. Potential cost savings are upwards of 60% by reduced O&M costs, and increased production efficiency, meaning an estimated reduction for O&M from €2400 to €960 per MW installed capacity per year. As the installed capacity of offshore wind energy in the EU is expected to grow from 10 GW (2017) to 46 GW (2025) and finally 68 GW (2030), 7 the potential for cost reduction in manual O&M operations through Unmanned Aerial Systems (UAS aka Drones) can be projected at 100 M€ per year."

Following the top-down perspective, the business goals of a maintenance strategy that is based on the application of the AIRTuB drone should be derived from a clearly defined underlying vision which in turn depends on which wind farm the AIRTuB drone will be deployed at. If the Amalia wind farm serves as a reference, then additional information regarding the currently applied maintenance strategy must first be provided as reference.

<u>Main research question</u>

How do the benefits, costs and risks of inspection (and repair) methods with the AIRTuB drone compare to those of the current inspection methods of the Amalia wind park?

<u>Sub questions</u>

- *What types of failure have occurred during the current service life and what consequential damage have they had?*

- *Which measures have been taken? Which inspection and repair techniques have been used? What Asset Management (AM) strategy has been followed?*
- *Which AM strategy is foreseen for the remaining life? What is the estimate of the future damage pattern? What is the estimate of future developments in terms of inspection and repair?*
- *What are the advantages and disadvantages of the current inspection techniques?*
- *What are the business goals of using the developed automated blade inspection technology of the AIRTuB project?*
- *What are relevant predictive maintenance performance indicators?*
- *What are the concrete input data of the two baseline scenarios for the business case comparison?*
- *What are the inspection options of the innovative AIRTuB drone?*
- *What are the differences and similarities with the drones currently used at the Amalia park?*
- *What are the advantages and disadvantages of using the new AIRTuB drone for inspection?*
- *What are the concrete input data of the new AM strategy scenarios for the business case comparison?*
- *What sources are used for the input of the business case?*
- *How is the business case/ cost analysis of the scenarios constructed? what is included and what not?*
- *How is the validation with experts been done?*
- *What are the results of the business case and the sensitivity analysis?*

Report Wp 7 Business case report (HZ, TNO, Stork (2022) contains a complete overview of the answering of all these sub questions. Here only the most essential parts are covered, with a focus on the results of the cost comparison of the three maintenance scenarios as that is considered to be the core of WP7.

2.4 Work method

- A global to refined approach has been adopted;
- The original AIRTuB project plan (Field Lab Zephyros (2019)) has been used as basic reference to define the research question. However subsequently, the current status of the project and new developments in the field were examined and the research and in particular the scenarios to be considered were adjusted accordingly, see introduction chapter;
- To be able to evaluate the various maintenance strategies effectively, first a back to basics approach of a risk and data-driven working method has been followed by starting with a failure analysis of the wind turbine blades. Largely similar to the FMECA/RCM method that is commonly used in practice.
- Subsequently, the possible quantification of the relative probability of failure and the consequences of the various failure forms have been examined, and finally the actions/ measures to control and/ or effectively reduce the risks have been considered. Various inspection options and repair methods have been examined. The latter mainly focused on condition-based maintenance because this is mainly used for the maintenance of the turbine blades.. Sources of information: literature study, desk research, interviewing experts, data analysis Amalia Park

- A mixture of a qualitative and quantitative approach has been used, depending on the topic, the availability of information and its reliability;
- The HZ contribution is considered to be the first part of the total investigation into the most suitable maintenance strategies for the turbine blades. Emphasis has been put on providing a good basic input and obtaining a good overall results overview. The output has been limited to a global (cost) analysis of the baseline scenarios and the new scenario 1. In addition, TNO has made a more refined and accurate cost calculation with advanced simulation software. The outcome of both have been used to validate both approaches. In addition, the results have been reviewed by experts.

Results/ deliverables

Results in short, based on the requested deliverables:

(1) Business goals of developed automated blade inspection technology of AIRTuB project: see previous introduction.

(2) Develop and compare the three updated scenario's, including:
 - Benefits analysis

Baseline 1: Manual visual inspection via rope access:

Table 2.3: SWOT on baseline 1, rope access inspection

Strengths ● In practice the inspector makes a pre-selection and prioritizes during the inspection, focusing in particular on category 3-5 damages. The photos are often of good quality, showing the damage well.	**Weaknesses** ● at the same time the pre-selection is an also disadvantage as the inventory is often far from complete as a lot of minor defects have not been inventoried making it difficult to get a solid complete overview of the condition of the blades. ● Only visual inspection data, no laser scan or ultrasonic scan of possible internal damages. (visual inspection of inside of blades is only possible to a limited extend (also depending on size of blade)) ● H&S risks are high ● Time consuming (and as a result also more hindrance due to bad weather days, less efficient, more downtime etc.), labor intensive, and therefore probably expensive ● Variability in maintenance quality
Opportunities ● Competition between service providers decreases price	**Threats** ● Ongoing innovations/ improvements of drone inspections. In comparison further optimization of rope access inspections is relatively limited and/or less effective.

Baseline 2: Visual inspection with current 4k camera drones:

Table 2.3: SWOT on baseline 2, currently used 4k camera drone inspection

Strengths ● Drone inspections are most likely to be more cost and time efficient than via rope access ● Increased window of time for inspection of the wind generator blades ● The data records are rather complete as the drones make pictures of (almost) the total surface of the blades ● Data records of blade erosion over time allowing for improvement of maintenance strategy.	**Weaknesses** ● Only visual inspection data, no lasers can or ultrasonic scan of possible internal damages. (visual inspection of inside of blades is only possible to a limited extend (also depending on size of blade)) ● The quality and/or clarity of the pictures is at times insufficient. Also, no information about the depth of damages is available; alltogether leading to mistakes and inefficiencies.
Opportunities ● Major decrease on labor costs for manual inspections ● Enhance staff safety and decrease in O&M costs ● Data collection and analysis has the potential to decrease AEP (Annual Energy Production)	**Threats** ● Operation of drones may require additional safety certifications ● Ongoing innovations

Table 2.4: SWOT of new scenario 1, inspection with AIRTuB drone

Strengths ● Drone inspections are most likely to be more cost and time efficient than via rope access ● Increased window of time for inspection of the wind generator blades ● The data records are rather complete as the drones make pictures of (almost) the total surface of the blades ● In addition to currently used drones: (1) by using additional laser scan depth of damages can be better estimated; improved quality of inspection, more efficient repairs (2) by using ultrasonic scan, the internal condition of the blades can be inspected. ● Data records of blade erosion over time allowing for improvement of maintenance strategy.	**Weaknesses** ● Still in early stages of development - No proof of market and at this moment still needs to be tested in real-life offshore conditions ● Substantial R&D costs ● Due to relatively large size of drone to transport a SOV instead of a CTV vessel is needed
Opportunities ● Major decrease on labor costs for manual inspections ● Enhance staff safety and decrease in O&M costs ● Automating data collection and analysis ● More refined modelling deterioration process of blades, better description pf-curves, more accurate estimation required inspection and repair frequencies. In addition, has the potential to decrease AEP (Annual Energy Production)	**Threats** ● Operation of drones may require additional safety certifications ● Ongoing innovations (of competitive alternative drone designs)

(1) Cost analysis

Used input for each scenario: see *Wp 7 Business case report report* (HZ, TNO, Stork (2022)

Output cost comparison: see table previous table 2.2.

(2) Sensitivity/ risk analysis

In principle here, a sensitivity study to verify the robustness of the above cost comparison of the three inspection variants will be realized by the additional more detailed cost analysis of TNO.

Comparison direct cost of yearly surface inspections **Sensitivity study**
In principle here, a sensitivity study to verify the robustness of the above cost comparison of the three inspection variants has been made by the additional more detailed cost analysis of TNO, see following chapter.

Uncertainty input parameters
However, besides the limitations due to the rather simple and limited set-up of the calculation model and the need of a more advanced approach as done by TNO, as said a most likely more significant challenge is to cope with the relatively large uncertainty of the used input parameters.

Globally speaking the used starting points in the current analysis have been arguably more in favor of the drones. As said changing the values of the following input parameter largely influences the outcome:

- number of WTBs inspected via rope access, 1 or 2 per day?
- Number of WTBs inspected with the drones, 10 or only 5?
- CTVs used for rope access and nr of teams per day?
- CTVs used for drone inspection and nr of drones per day?

Changing of the input parameters with relatively more favorable (upper limit) values for the rope access scenario (also based on meeting with A. Dever and B. Vandehoek, Eneco, on 9 December 2022):

- Rope access inspection of 2 WTBs per day;
- Only 5 WTB inspections per drone per day (both baseline 2, and new scen. 1);
- 1 CTV used for ropes access per day, 4 teams per day;
- 2 vessels used for drone inspections, 1 drone used (unchanged).

Changed results with the above adjusted input:

Table 5.4 Output calculation of total direct inspection costs of the three scenarios, based on the above changed input parameters

	Total costs
Baseline 1	€ 239.000
Baseline 2	€ 194.400
New. Scenario 1	€ 251.400

AIRTuB

As can be seen the differences between the three scenarios are now much smaller. A huge impact has obviously the inspection time of rope access (1 or 2 WTB per day), which in turn depends on the weather conditions. This also clearly shows the downside of the rope access: there is a relatively largely depency on the weather conditions as the inspections are clearly more time consuming than those with the drones. And certainly in future this difference will further increase as drones will develop further and will most likely be operating faster. The second important influencing parameter are the transport costs per scenario. Now of course with 4 rope access teams transported by 1 CTV these costs drop significantly. However when using more drones these costs will subsequently also drop for the drone inspection drones (the costs of the drone scenario's in table 5.5. are still based on just using 1 drone, while the rope access inspection is done by 4 teams). So although as can be seen from table 5.5. with more favorable starting points for the rope access inspections the difference in inspection costs drop significantly, the costs of the rope access inspections works contain relatively more uncertainty.

To be complete and to obtain a fair comparison, other remaining uncertainties regarding costs that are not included in this:

- the material costs, the AIRTuB drone might be more expensive;
- the labor costs (on the long-term unfavorable for the rope access approach);
- the exact extra costs due to inefficiency of the O&M costs when using the 4k camera drones, see further explanation below;
- Moreover, significant other additional costs like extra downtime of the WTB during due to extra inspection and repair time has not been included as here only the direct costs are considered.

As mentioned above in practice the main disadvantage of using the current 4k camera drones is that mistakes are being made with the classification of damages due to the at times poor quality of the images. <u>That is still an important drawback that should not be overlooked.</u>
This leads to quite some inefficiency at the repair works, which is not yet included here. Due to the lack of accurate data/ information it is difficult to estimate how much these additional costs are. If these extra repair costs are really significant, then inspection via rope access can still be competitive when compared with the current 4k camera drone inspections.

The latter makes also clear what the big potential improvement is of using the AIRTuB drone: although more expensive in use than the current 4k camera drones due to the higher transportation costs (too big and heavy, therefore a SOV instead of CTV is needed), the high-quality data is expected to prevent the extra repair costs due to inefficiency.

In fact, also compared to the data gathered by visual inspection via rope access, the quality of the data is much higher and more complete so that the repair works can be further optimized in comparison and most likely be reduced. Taken this into consideration, the AIRTuB drone emerges as the best. Moreover, as said further optimizing is to be expected as most likely the crawler can become lighter and smaller in future, and this will also apply to the AIRTuB.

Risks: see report *Wp 7 Business case report* (HZ, TNO, Stork (2022), and par 2.5..

(3) Validation by experts.

Results have been reviewed by Jos Gunsing (Marotech), and Eneco (Bart van de Hoek, Andrew Dever). Furthermore, feedback has been gathered during intermediate presentations of results during Airtub related meetings and events. And the cost calculations of HZ and TNO have of course been compared with each other for calibration.

(4) Overview of corresponding predictive performance indicators.

Obviously the most significant difference between the O&M works of on- and offshore wind farm is the difficult accessibility of the offshore farms. This indicator plays a decisive role in the maintenance works of offshore wind park, and from a more abstract view, on the availability of the park. Globally, the latter in turn is key when it comes to measuring the performance of the park. The figure below shows the essential KPIs of offshore wind park and their mutual relationship.

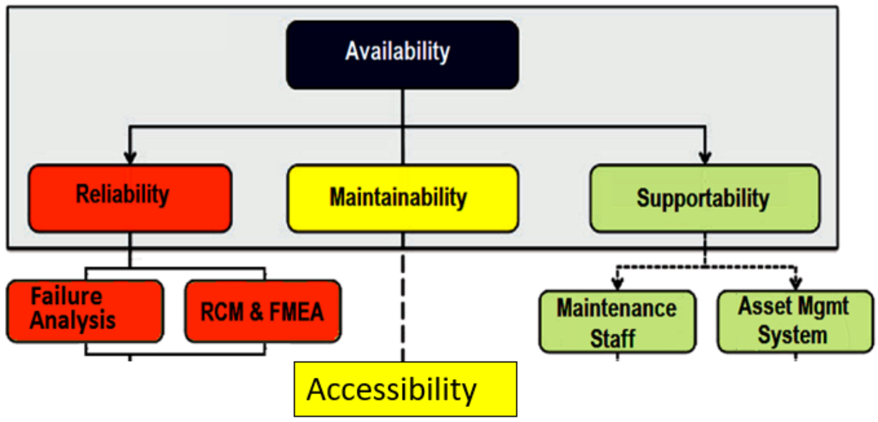


Figure 2.1: Relation between availability, reliability, maintainability and supportability

Some examples to improve these kpi's:

- Reliability: (improving) component reliability, upscaling, lean design
- Maintainability: smart diagnostics, data driven/ condition based, optimizing A&M works
- Accessibility: reducing travel time, offshore basis (HUB), better transport facilities
- Supportability: zero on-site maintenance, remote sensing.

Much of these are related to or can be achieved by optimizing the O&M with the advanced automated sensor- and -coating systems of the AIRTuB project.

Possible spin-off and follow-up activities

- Offshore testing of drone;
- Further developing repair abilities of crawler;
- Optimizing (automated) analysis of failure data;
- Studying/ making inventory of failure data of other Wind Parks;
- Developing of (more) refined (statistical and/ or physical) models to better predict deteriotian/ aging of blades, Pf-curves, better estimation of required inspection and repair frequencies/ life time extension prediction;

- (Adapting to) new/ ongoing innovations regarding inspection and repair. Optimizing weight of drones;
- Using HUB to optimize O&M;
- Expending scope of cost analysis (when more information becomes available, incl. the corresponding sensitivity study);
- Etc.

2.5 Discussion and conclusions

- Costs of rope access inspections are higher than those of the drone inspection, especially when based on initial input parameters (see also results of sensitivity study);
- Rope access is more time consuming, so more inspection days are needed, resulting in more transportation, higher vessel costs, more hindrance from bad weather days;
- Moreover, significant other additional costs like extra downtime of the WTB during due to extra inspection time has even not been included;
- Main disadvantage of using the current 4k camera drones is that mistakes are being made with the classification of damages due to the at times poor quality of the images;
- The (expected, not yet fully tested offshore) advantage of the laser (line) scanner of the AIRTuB drone is that the high quality data will prevent these extra repair costs due to inefficiency. Furthermore the ultra sonic scanner gives the ability to scan possible internal damages of blades giving a more accurate and complete overview of the total condition of the blades. In future this may lead to a better prediction of possible life time extension of blades which can be very profitable;
- From a health and safety perspective, it's obvious that blade inspections and repair activities via rope-access require special attention
- Risks in the sense of threats to be outpaced by alternative solutions in the (near) future: current developments are moving fast and the question is if the AIRTuB drone will be the final solution
- An obvious risk that is currently still valid is that it is still uncertain how the AIRTuB drone will perform in the real world. An obvious risk that is currently still valid is that it is still uncertain how the AIRTuB drone will perform in the real world, also with respect to its foreseen repair capacities (for instance the need to sand, fill, sand, potentially apply promoter, & apply LEP is a considerable demand).

2.6 Recommendations

- Consider the previous overview of possible spin-off and follow-up activities
- Stay on track with, monitor constantly ongoing developments and innovations with in the field of O&M works and respond to this when further developing the Airdrone drone (in AirTuB 2). Check if the starting points and input used in this study needs to be updated accordingly. Similar to this, when further working out the cost analysis of the remaining New Scenarios 1b, 2 and 3 , this of course also applies to the impact of continuous developments of existing and new repairs techniques. As for the foreseen repair capabilities of the Airtub crawler which may be further investigated and developed in the follow-up project Airtub 2: a point of attention is answering the question whether the 'crawler' can be used to repair the current LEP resources. The need to sand, fill, sand, potentially apply promoter, & apply LEP is a considerable demand. So much perhaps that the crawler proves to be of value only on blades without the current LEP. Furthermore weather restrictions for flight, landing, attachment and repair should be seriously be considered to obtain a realistic view on the repair capabilities of the crawler.
- To obtain a more complete overview, extend the cost comparison when more information/ data becomes available . Now only the the direct costs of inspection and repair are considered. However, for a complete (and fair) comparison, it will be necessary to zoom out and also take a look at things such as discounting the development costs of the new techniques, etc. A very important aspect in this regard is **of course to determine what the exact influence of the automation of maintenance is on the actual main objective: to increase the (annual) energy production of the wind farm**. In the TNO O&M planner analysis this has been considered by comparing the KPI *Wind farm yield-based availability (%)* of the maintenance scenarios. Due to the lack of sufficiently accurate available data in this current study this has not yet been converted to costs. However, this is most likely to be a big(ger) financial impact and it is therefore strongly recommended to include this in a future study.
- Consider the growing shortage of personell, especially with regards to rope access inspection. In addition to the resulting need for further automation of maintenance (as the work cannot be done manually due to lackage of personnel), there is also a good chance that wage costs will rise (significantly) in the (near) future as a result, which has not yet been implicitly included in this study.
- Consider the relative uncertainty of the estimated costs in addition. Up till now, the main challenge has been how to deal best with the relatively lack of data, information regarding the actual damage history of the wind turbine blades of the Amalia Wind Park. This gives relatively much uncertainty regarding the actual condition of the blades, the forecast of future damages, the required inspection frequencies and in particular regarding the estimation of the repair costs. In the current analysis of baseline 1,2 and new scenario, the latter has only been considered to a limited extent, mainly qualitatively. But when considering the additional remaining new scenario's 1b, 2 and 3 more in detail, the quantification of the repair costs as a result will most likely contain a relatively large amount of uncertainty. To obtain a realistic picture of the actual total costs, it is therefore recommended to take these uncertainties into account by means of an additional sensitivity analysis (, including an evaluation of the influence of upper and lower boundary limits of the main cost-determining parameters).

3 Execution of the project

- The problems (technical and organizational) that occurred during the project and the way in which these problems were solved

See description of changed scope in Chapeter 1 Summary. Main problem has been lack of accurate data/ information, particularly with respect to damages/ actual failure behavior of blades (LEE, but also other failure modes), limited information about actual repair works (At Amalia Wind Park, the difficulty that at the Amalia Wind Park over time several different repair techniques (LEP9, BASF, Polytech Shells) have been used and that only limited information of each was available. Furthermore it seems that after the installment of the Polytech Shells LEE no longer occurs although there is still uncertainty about the performance of these shells on the long term (no information available let). This was dealt with by focusing for now in particular on the inspection aspects of the O&M works (as the latter could be much better estimated). Furthermore a very useful source to validate the used research input has been Mr. Andrew Dever, a very experienced senior in the field of O&M works of offshore Wind Parks.

- Explanation of changes to the project plan

See description of changed scope in Chapeter 1 Summary.

- Explanation of the differences between the budget and the costs actually incurred

The differences are relatively small. Partly because timely decision has been made about how to deal with the lack of available data, and by working efficiently from global to refined, also by having brief biweekly meetings with the WP7 team to monitor the progress.

- Explanation of the way of spreading knowledge

The HZ research results are and will be further processed in the HZ HBO education. E.g. in the course material of the HZ offshore renewable energy minor, HZ (Civil and) Engineering Programme, also via guest lectures.

- Explanation PR project and further PR possibilities

(Intermediate) results of WP7 have been presented on several Airtub meeting and events. HZ has provided the input and feedback. Further PR possibilities are possible (and have already been processed in the corresponding HZ HBO education programmes, and new future research projects (for instance Airtub 2).

4. Reference list

The reference list of the *Wp 7 Business case report* , incl. the sources mentioned in this current report.

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