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The Impact of Maintenance and Technology Change on Remanufacturing as a Recovery Alternative for Used Wind Turbines

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Abstract

In the wind power industry, maintenance and technological evolution/improvement are critical factors to ensure low operations and maintenance (O&M) costs and keep the wind turbine (WT) available to generate power. In addition, these factors are critical in facilitating product recovery through remanufacturing at the end-of-use (EOU). Under a system dynamics (SD) approach, the interaction between maintenance, reliability, and technological obsolescence on the remanufacturing of a wind turbine was modeled. Findings suggest that regular preventive maintenance might avoid/slow functional obsolescence, and as a result, the remanufacturing cost is reduced. Technological change could lead to technological obsolescence. Both types of obsolescence might increase the overall remanufacturing cost. An increased remanufacturing cost will affect the attractiveness for recovery and profits obtained from original equipment manufacturers and the savings in the initial capital investment made by secondary customers.

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Keywords: Wind Turbines; Value Recovery; Remanufacturing; End-of-Use; Sustainable Manufacturing; Maintenance; Technological Obsolescence

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1. Introduction

The wind power industry is growing fast, the need to prepare for the end-of-use (EOU) of wind turbines (WTs) is gaining importance and has been explored in a previous study [1]. Remanufacturing is a promising alternative to recover functional as well as material value from used WTs and develop a circular economy for the wind power industry [2]. Maintenance and technological obsolescence are critical in determining not only the WT performance but also the value of product recovery at EOU. The objective of the present work was to study how the operation and maintenance (O&M) and technological change impact the recovery of value from used WTs over time and specifically, the cost of remanufacturing. Maintenance is the act of maintaining a product by either keeping it in an existing state or preventing it from failure or decline [3]. The paper aims to address these issues in detail as follows: in sections 2 and 3 a model for how O&M and technology evolution influence recovery at EOU are described. In section 4, results regarding the impact of O&M and technological change on a 2MW WT are presented. Summary and directions for future work are provided in section 5. The nomenclature considered in the paper is shown in the inset.

Nomenclature

CM	Corrective Maintenance
EOU	End-of-Use
EOUWTs	End-of-use Wind Turbines
OEM	Original Equipment Manufacturer
O&M	Operation and Maintenance
PM	Preventive Maintenance
WT(s)	Wind Turbine (s)

Assumptions made in the paper are provided below:

- A Weibull distribution has been used to describe the reliability of the WT as it ages and wears. Shape and scale parameters for each sub-system were retrieved from the literature [4].
- A WT behaves as a serial system. If any of the sub-systems fail, the entire system fails. The reliability of the system is the product of individual sub-system reliabilities. The failure rate of the system is the sum of individual sub-system failure rates.
- Maintenance is performed at an interval T=0.5 year, restoring the system to a condition between “as-good-as-new” and “as-bad-as-old”.
- Criticality values of each sub-system were assumed based on authors’ experience.

2. Value Recovery: Maintenance Model

Maintenance is critical in keeping low O&M costs, guaranteeing energy production as well as facilitating the recovery at EOU. In the case of WTs, due to the relatively recent introduction of the technology, the availability of data related to reliability of WTs older than 10-15 years and WTs with a rated power higher than 1MW is very limited. There is not a clear understanding of failure behavior for a complete WT life cycle [4, 5]. Presumably, early failures occur during the first years (1-6yr), then a long period of random failures with a constant rate takes place (6-15yr) until failures start to increase with age and wear (>15yr) [5, 6].

It is believed that frequent preventive maintenance (PM) during the useful life results in a lower level of product degradation at EOU. PM improves the system performance in terms of reliability and availability. A higher reliability at EOU leads to a lower remanufacturing effort to make the product “as good as new” and reduces the remanufacturing cost (Figure 1). A reduced remanufacturing cost improves not only the profit margin obtained by the OEM when selling the remanufactured WT but also the project economics for secondary users.

The SD model (See Appendix A) estimates the WT reliability with and without PM. Each of the estimated reliabilities was used to determine the remanufacturing cost at EOU as well as the cost of corrective maintenance (CM) regarding sub-systems replaced after failure. Likewise, the opportunity cost due to downtime in which the WT is not generating electricity was also estimated.

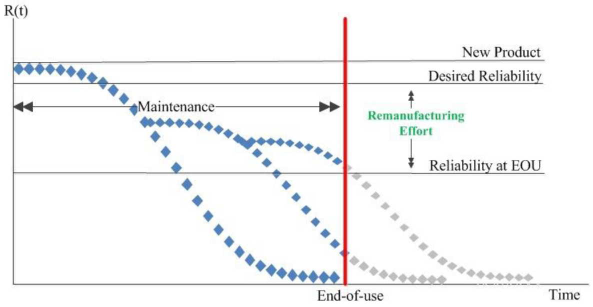


Figure 1. Remanufacturing effort as a result of the gap between the reliability at EOU and the desired reliability for the remanufactured WT.

2.1. O&M and Wind Turbines

O&M data for WTs varies across sources of publications. The main differences are in terms of WT topologies and sizes, location, environment conditions, period, and methodology of analysis [5, 7, 8]. A summary of O&M indicators is presented in Table 1. Typically, WTs have a 2-year maintenance contract with the OEM. During this period, any corrective or preventive maintenance is covered by the OEM. WTs are serviced twice a year. The PM takes 60h per year and requires 4 technicians. The O&M cost is approximately $10,780 per year per WT [9]. Hourly rates for technicians vary between $31 (junior technician) and $49 (senior technician) and depends on skills and local labor markets [10]. For the purposes of the SD simulation, a cost per technician-hour of maintenance or repair was assumed to be $45/tech-h.

Table 1. WTs' Sub-system O&M Typical Indicators (scale and shape parameters used for Weibull calculations) [6, 11, 12].

Sub-assembly	λ fails/yr.	MTBF (h)	RT (h)	NR	Scale (θ)	Shape (β)
Rotor system	0.19	39,297	96	4	20	2
Generator	0.11	73,234	174	2	17	3.5
Gearbox	0.09	87,174	150	2	12	3
Control system		39,205	46	4	12	2
Main shaft	0.02	365,339	132	-	25	3.5
Hydraulic system	0.1	79,363	24	2	12	3.5
Yaw system	0.11	69,604	60	2	12	3.5
Electrical system	0.3	25,708	36	6	20	2
Pitch system	0.09	90,472	60	2	10	3.5
Air brake	0.04	180,078	72	1	10	2
Mechanical brake	0.03	223,447	96	1	10	2

λ = Failure rate; MTBF = Mean time between failures; RT = Repair time; NR = Number of replacements during lifetime (NR = Total hours available during lifetime/MTBF).

Larger WTs with pitch control, mechanical brakes, and direct drive with a synchronous generator tend to have higher failure rates [5]. The sub-systems with the highest frequency of failure are the electrical system, control system, hydraulics, and rotor blades [6, 13]. The sub-systems with the highest severity of failure (i.e., longest downtime) are the gearbox, generator, drive train, and rotor blades [11, 14]. There are two alternatives when a sub-system fails: repair or replacement. In this study, it was assumed that main sub-systems are replaced when they fail. Thus, the effective age and reliability of a WT at EOU might be a combination of sub-systems with varying ages or periods of operation [4].

2.2. O&M and Remanufacturing

The role of maintenance in terms of affecting reliability has been previously explored by Lewis [15]. The reliability of a maintained system was estimated using Equation 1.

$$R_M(C_i) = \exp\left[-N\left(\frac{t}{N\theta}\right)^{\beta}\right]\times\left(1-p\right) \qquad (1)$$

In the SD model (See Appendix A), a Weibull distribution was used to represent the reliability of each maintained sub-system (C_i), where the maintenance is performed at an interval of T (e.g., T=0.5 yr). N=t/T, is the number of maintenance operations carried out per year, and p is the probability of a maintenance failure each time maintenance is performed. The cost of maintenance is estimated based on the number of hours consumed per each service. When a sub-system fails, it is replaced. The corrective maintenance cost is estimated based on the replacement cost of failed sub-systems. Additionally, the opportunity cost of not generating electricity was tracked. At EOU, the reliability gap between a maintained system and the desired reliability for a remanufactured WT was estimated. In this study, it was assumed that the desired reliability for a remanufactured WT is (0.95).

Regarding the gap between the actual and the desired reliability, a functional relationship for the time required for the remanufacturing process was established. The current lead time for the delivery of a new WT is around 12 to 16 months; it is expected that a remanufactured WTs will have a shorter lead time [16]. A reliability gap smaller than 0.3 will require 3 months for the remanufacturing process, a gap between 0.3 and 0.7 will require 6 months, and a gap higher than 0.7 will require up to 9 months. Thus, the higher the gap, the higher the effort required for remanufacturing. It was assumed that the remanufacturing process might take up to a maximum of nine months with 6 technicians and a cost per technician hour of $45.

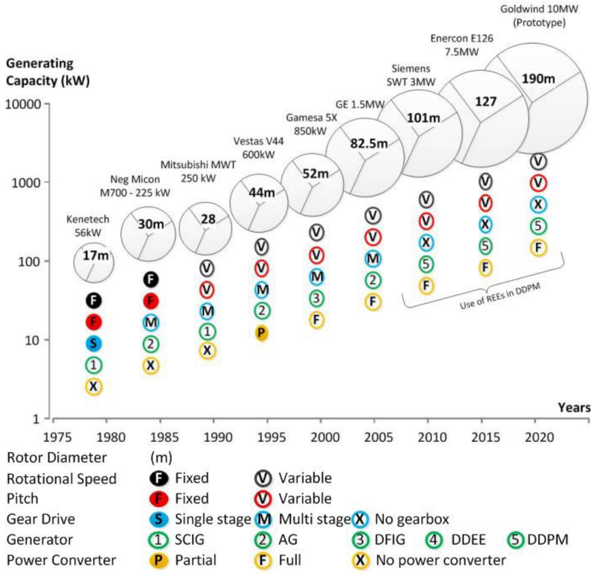
3. Value Recovery: Technology Change Model

Classically, the development of any new technology proceeds slowly at its inception due to uncertainty or lack of understanding of the technology's fundamentals. Then, a period of increasing growth comes as a result of a "consensus" about the designs, performance, attributes, or service conditions. During this period, effort focuses on market growth, standardization, process improvement, and cost reduction. Later, new innovations emerge and older technology starts to reach a steady state in the market until it is finally displaced by yet another new technology. When a product loses its ability to perform its function competitively, the product is termed as obsolete and loses its value. The typical shape of this technology life cycle is referred to as a S-curve [17]. WTs are in the growth period of technology development as explained in the following sections. In the next decade, WT technology will enter the steady state and some units will start reaching their EOU phase. The technology change analysis intends to understand how this evolution of technology and the gap between new and old WT technologies might affect remanufacturing as a potential alternative for value recovery.

3.1. Technology Evolution of Wind Turbines

Although WT technology has evolved over time, the design life has remained close to 20 years. The widely accepted industry technology consensus for onshore WTs includes: horizontal axis, three blades, fixed or variable pitch, fixed or variable speed, geared or direct drive, and synchronous or induction generators. A comparison of WT configurations over time was developed and results are presented in Figure 2. Nine WTs models from different OEMs were compared.

1980: Kenetech 56kW
1985: Neg Micon M700 - 225 kW
1990: Mitsubishi MWT 250kW
1995: Vestas V44 – 600kW
2000: Gamesa AE 59 - 800kW
2005: GE 1.5MW
2010: Siemens SWT 3MW
2015: Enercon E126 – 7.5MW
2020:Goldwind 10MW (not commercially available, half DD)



SCIG=single cage induction generator; AG= Asynchronous generator; DFIG=Doubly-fed induction generator; DDEE=Direct drive with electrical excitation; DDPM= Direct drive with permanent magnets; REEs=Rare earth elements.

Figure 2. The Evolution of Wind Turbine Technology shown as a function of Generating Capacity (kW) for the years 1980 to 2020.

The figure indicates that the latest WT designs have more than 1MW rated power, greater than 80m of rotor diameter, variable rotational speed, variable pitch system, multi-stage gearbox or gearless, doubly-fed induction or permanent magnet generator, and full power converter. The best configuration is still not clear. WT technologies seem to evolve as a new set of mixed attributes rather than through new product generations. Likewise, characteristics such as tower height, rotor diameter, and service plan might be chosen by a customer according to their needs.

In the U.S., the evolution of the wind power industry has also been shaped by renewable energy policies as well as by market and economic conditions. Figure 3 presents the timeline from 1985 to 2010. The cumulative installed capacity has grown by 3600%, the number of WTs and their rated power increased by 3.8 and 30 times respectively. Likewise, the installed cost and cost of electricity were reduced by 40% and 77% respectively. Information was retrieved from the AWEA database [18].

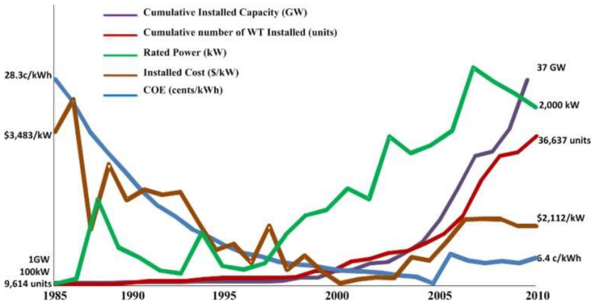


Figure 3. U.S Wind Industry Change Over Time (Source: AWEA database).

3.2. Technology obsolescence and Remanufacturing

Technology obsolescence affects the customer purchase decision. When purchasing a remanufactured WT, three characteristics are critical: price, functionality, and product condition [19]. The price of remanufactured products has been explored previously [19-21]. Experience with other remanufactured products indicates that when the price of a remanufactured product exceeds 70% of a new product, customers likely will prefer the new product instead of the remanufactured one. Functionality and condition are closely related to age and reliability of the product. The original product's age and features determines whether the product still fits the "industry consensus" design or not. The effective age of a WT and its reliability at EOU, depend on whether sub-systems have been replaced either during the first useful life or during the remanufacturing process. The effective age [22] of a remanufactured WT was estimated using Equation 2.

$$E_{age} = L - \sum C_i \times (L - A_{i_{rep}}) \tag{2}$$

Where, L is the WT design life, C_i is the criticality of the ith sub-system, and A_{irep} is the age of the ith sub-system (i)-based on the time of last sub-system replacement (See Appendix B). The WT's reliability will be the product of individual sub-system reliabilities $R(C_i)$, where the sub-systems reliabilities consider replacements made during the useful life and critical components that are replaced during the remanufacturing process (i.e., generator, gearbox, main shaft, and control system).

4. Impact of O&M and technology change in Value Recovery of EOUWTs

The system dynamics model predicts the long term impact of maintenance on reliability at EOU and value recovery of the used WT. If no PM is done, then more system failures are likely to occur (16 faults on average during a WT's useful life). At EOU, these failures caused a total downtime of 1,006h during the use cycle with a total replacement cost of $500,033. Additionally, the opportunity cost of not generating electricity during the downtime is $11,563. The reliability goes down quickly and gets close to zero prematurely at around year 11. Failures degrade the system performance and the quality condition at the EOU resulting in additional time and labor required to remanufacture the WT to reach a "like new" condition. A non-maintained unreliable used WT will require 3 additional months for remanufacturing and to reach the desired level of reliability (i.e., 0.95) than if the WT system was maintained twice per year.

Undertaking PM twice per year reduces the gap between the level of reliability desired and that obtained at EOU by 21%. This is due to an increase in the reliability at EOU from 0.12 (with no PM) to 0.3 (with PM). A lower gap (0.65) will require only 6 months for remanufacturing. Thus, the remanufacturing cost is 33% less costly than if no PM is pursued. The absence of PM increases the remanufacturing cost and might compromise the economic benefits that can be realized by an OEM and secondary users. The results of the SD simulations are summarized in Table 2.

Table 2. WT Remanufacturing Cost with and without Preventive Maintenance (PM).

	Without PM*	With PM twice a year*
Number of failures	16	1
Downtime	1,006 h	96 h
PM Cost	0	$67,545
CM Cost (replacement)	$500,033	$9,702
Opportunity Cost	$11,563	$293
Reliability at year 20th	0.12	0.30
Time to adjust the reliability gap	2,160 h	1,140 h
Remanufacturing Cost	$231,770	$154,513

* Values estimated for a WT during its useful life. Present values regarding 2% inflation and 7% discount rate.

To examine the dependence of the net present remanufacturing cost to changes in the different system variables, a sensitivity analysis was performed. The results indicate that a desired level of reliability between 80-100% does not impact the remanufacturing cost because the time required for reprocessing will still be 6 months for both 80% and 100% reliability. However, an increase in labor related variables (personnel and cost per hour) could increase the cost up to 66%. Likewise, if the probability of faulty maintenance operation increases to 1%, the remanufacturing cost will rise up to 30%. Lastly, a greater discount factor will result in a lower remanufacturing cost, approximately 44% lower that the reference value ($154,513).

The technology gap between older and modern WT models affects the recovery of value from remanufactured WTs not because of functional obsolescence but instead because of "market" obsolescence. Maintenance and replacements made during the useful life reduce this gap. Due to the highest frequency and severity of failure, it was assumed that the generator, the gearbox, main shaft, and control system are replaced at the time of remanufacturing.

Sub-systems such as the tower, nacelle, nose-cone, bedplate, and hub are remanufactured. With such an operating strategy, a used WT could be remanufactured in only six months. The effective age of a remanufactured WT at year 20 would be approximately 5.5 years. Likewise, its reliability would be approximately 0.95 after the remanufacturing process. Under these conditions the remanufactured WT is completely functional (i.e., not functionally obsolete) and the likelihood of the WT being re-commercialized is higher. The value proposition of EOUWTs recovery is attractive. The obsolescence is not caused by a diminished performance but instead by market perceptions and expectations relative to new designs.

5. Summary and Future Work

An analysis of the effect of maintenance and technology evolution on value recovery of wind turbines at end-of-use has been conducted. Findings suggest that regular maintenance twice a year has a positive impact on reliability at EOU. The gap between the actual and desired reliability is reduced by 21% with PM. As a result, the time required to restore a used WT is shorter (6 months versus 9 months for a no maintenance scenario). Even though WT technology is changing over time, maintenance and replacements during the remanufacturing process make recovered WTs functional, reliable, and non-obsolete because after one first period of useful life they still largely meet industry expectations.

Further work is required to characterize accurately the criticality of sub-systems as well as their characteristic life and replacements during useful life. This study could also be broadened to include technology evolution of offshore WTs and vertical axis WTs and their impact on remanufacturing at EOU.

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Appendix A. System Dynamics O&M Model

The causal diagram shown in Figure 4 is a simplification of a more complex SD model that has been developed for the whole system. The arrows are labelled with a + or - to indicate a positive dependence or a negative dependence between variables. For example, an increase in the PM frequency results in an increased WT reliability (positive dependence), and an increase in reliability with PM reduces the failures (negative dependence).

Figure 4 shows that improving the reliability of the WT through PM, reduces the gap relative to the reliability desired for a remanufactured WT. A decrease in this gap, decreases the time required to perform the remanufacturing process and consequently, decreases the remanufacturing cost.

Improving the reliability of the WT through PM also reduces the number of failures. Fewer failures decreases the downtime resulting in a lower opportunity cost. Fewer failures lead to fewer replacements, and therefore, a lower CM cost. On the other hand, having no PM decreases the reliability over time and increases the gap. As a result, the remanufacturing cost is increased as well.

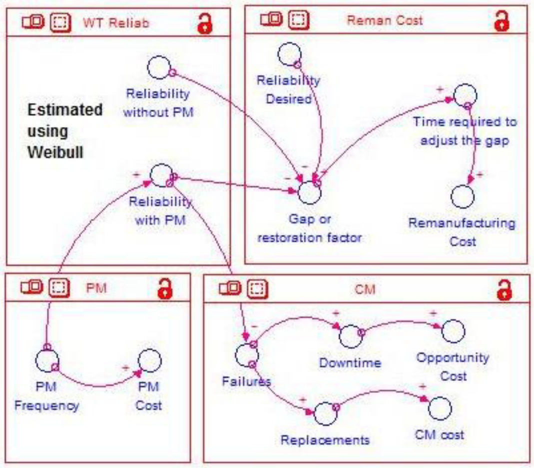

Figure 4. O&M Causal Diagram and its Impact on Remanufacturing Cost

Appendix B. Remanufactured WT Effective Age

Table 3. Estimation of a Remanufactured WT Effective Age

Sub-assembly	% Criticality (a)	Replaced during Reman	Remaining Life (L-A_{rep}) (b)	(a)x(b)
Tower	5%	No	0	1.0
Rotor system	10%	No	16	1.6
Generator	10%	Yes	20	2
Gearbox	10%	Yes	20	2
Nacelle	1%	No	0	0
Nose-cone	1%	No	0	0
Control system	10%	Yes	20	2
Bedplate	1%	No	0	0
Main shaft	10%	Yes	20	2
Hydraulic system	10%	No	10	1
Yaw system	10%	No	10	1
Electrical system	10%	No	17	1.7
Pitch system	10%	No	10	1
Air brake	1%	No	10	0.1
Mech. brake	1%	No	10	0.1
			Eff Age	5.5yrs

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