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Deliverable

D4.2 – Robustness of remanufacturing flange connections and stray current circuits simulation

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Executive Summary

Remanufacturing or reuse of wind turbine gearbox components has so far been limited to the regrinding of visually observed defects and micro pitting based minor wear at gear flanks.

Reuse of broken gears or broken bearings have not been the practise in the industry. It has also been typical practise that even functional and undamaged bearings are replaced as safety precaution during gearbox maintenance – due to the cost of removing and installing of the gearbox, in some cases reaching cost of a gearbox itself. Those procedures were derived from extremely high reliability and zero-defect principles in the market.

Additive manufacturing would be a new practice and substantial improvement for reuse of failed components in the industry. Replacement of the failed component with updated technology that mitigates specific problem would have significant role in minimizing future failure rate as well.

New materials, design, and repair methods for fretting corrosion failures in flange connections and stay current initiated bearing failures were created. Further on the improvements are directly applicable to new production as lifetime extension and high torque density enablers for more powerful wind turbines.

For fretting corrosion mitigation there was defined and tested a solution where friction coefficient at the joint could be improved with reconditioned parts at product level. For stray current, a simulation tool methodology was verified with a scaled demonstrator.

During the technical approval, the “premature failure” modes were understood and replicated by verified simulation models. By that knowledge, the remanufacturing methods can be specified and further on implement as offering for business

Deliverable leader:	Vili Ryynänen (FLE-FI)
Contributors:	Adam Klodowski (LUT) Pasi Paakkinen, Jari Toikkanen, Mikko Järvinen (FLE FI)
Reviewers:	Thomas Sølund (SPIN), Bernhard Peischl (AVL)
Approved by:	Athanasios Poulakidas, Irene Diamantopoulou (NCI)

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Definitions, Acronyms and Abbreviations

Acronym/ Abbreviation	Title
AM	Additive Manufacturing
FEM	Finite Element Method
SoA	State of Art
TFF	Tooth Flank Fracture
ML	Machine Learning

1 Introduction

1.1 Project Information

Despite the multiple advantages of products remanufacturing, being widely recognised as an effective means for transitioning to a more circular economy, there is still need for improved research and experimental observations, to improve traceability and reliability of the final products from end-users' perspectives, as well as enhanced impacts monitoring. The primary R3-Mydas objective is to develop a multi-actor framework, integrating innovative digital technologies (ML for process and quality control, marketplace, graph models for defects detection, digital twins), advanced mechatronics (AM, laser-cladding, automated disassembly/reassembly) and newly developed approaches from SSH (extended TAM/UTAUT models, ethics and legal framework), for functionally, environmentally and economically sustainable circular value chains for remanufacturing of energy goods at the factory level (Oil & Gas crankshafts – demo 1, E-vehicles batteries – demo 2, Wind turbines gearboxes – demo 3).

R3-Mydas will deliver unprecedented impacts throughout the targeted value chains, as follows: up to 60% time reduction in programming for remanufacturing; up to 20% increased product quality; up to 30% rework reduction [Demo 1]; up to 30% improved detection of tiny deviations from normal behaviour; up to 50% faster anomaly localization; up to 30% increase the number of different modality data streams handled; up to 20% faster fusion process [Demo 2]; up to 99% reusage rate; -90% prevention rate; -75% lead time; up to 85% raw material savings potential [Demo 3]. R3-Mydas will deliver a marketplace associating to each remanufactured product or services/component for remanufacturing a Digital Passport-like set of information, ensuring full traceability. Finally, a dedicated training programme will be designed and delivered by EITM, targeting the R3-Mydas project remanufacturing value chains (100+ training hours and 100+ diverse stakeholders engaged during the Project).

The deliverable is validated via torque transmitting capacity. In an application/gearbox level there is criteria for Nm/kg as target and on a component/material pair level an acceptance in based on the validated friction coefficient. Simulation environment, methods and technical solutions are accepted if those fulfils international standard requirements. Also, commercial feasibility as serial manufacturing costs and engineering effort for defined application is a key process indicator. Acceptance and material saving potential can be confirmed when technical capabilities are documented. Measured behaviour of a reference drivetrain for stray current should correlate to simulation for acceptance criteria.

R3-Mydas demo case 3: Wind turbine gearboxes (WP4) - Actual SoA: Remanufacturing of wind turbine gearbox components has so far been limited to the regrinding of visually observed defects and micro pitting based minor wear at gear flanks. Reuse of broken gears or broken bearings have not been the practise in the industry. It has also been typical practise that even functional and undamaged bearings are replaced as safety precaution during gearbox maintenance, due to the cost of removing and installing of the gearbox, in some cases reaching the cost of a gearbox itself. Further, today's circular economy is based on material and not product parts and complete elements, which implies the need for energy intensive processes to first recover materials, then produce new components out of it.

Table 1: The R3-Mydas consortium.

Number[1]	Name	Country	Short name
1(CO)	NETCOMPANY-INTRASOFT SA	Luxemburg	NCI
2	EUROPEAN FEDERATION FOR WELDING JOINING AND CUTTING	Belgium	EWF
3	EIT MANUFACTURING SOUTH SRL	Italy	EITM
4	FLENDER FINLAND OY	Finland	FLE-FI
4.1(AE)	FLENDER GMBH	Germany	FLE
5	AVL LIST GMBH	Austria	AVL
6	TALLERES MECANICOS COMAS SLU	Spain	TMCOMAS
7	SPIN ROBOTICS IVS	Denmark	SPIN
8	ASOCIATION DE INVESTIGACION METALURGICA DEL NOROESTE	Spain	AIMEN
9	LAPPEENRANNAN-LAHDEN TEKNILLINEN YLIOPISTO LUT	Finland	LUT
10	INFORMATION TECHNOLOGY FOR MARKET LEADERSHIP	Greece	ITML
11	DEEP BLUE SRL	Italy	DBL
12	CHAROKOPEIO PANEPISTIMIO	Greece	HUA
13	IKERLAN S. COOP	Spain	Ikerlan
14	ZIKNES TECHNOLOGY SL	Spain	Ziknes
15 (AP)	CSEM CENTRE SUISSE D'ELECTRONIQUE ET DE MICROTECHNIQUE SA - RECHERCHE ET DEVELOPPEMENT	Switzerland	CSEM

1.2 Document Scope

This deliverable is a part of R3-Mydas wind turbine gear box demo case 3.

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[1] CO: Coordinator. AE: Affiliated Entity. AP: Associated Partner.

State-of-the-art solutions will be benchmarked, focusing on commercial methods for repair, coatings or friction elements, for integrating data retrieved during the proposal preparation. Experimental test definitions to confirm the friction coefficient and robustness under fatigue loading.

Stray current simulation is not a straightforward problem to solve as it affects Multiphysics phenomena. Several methods may be implemented for this purpose and will be evaluated in this task, to finally select the proper simulation framework and develop additional demo-specific models, reference case modelling (MS drivetrain) and automated modelling techniques. Evaluation is generally high risk. Based on product structural documentation and formalized functional requirements demo specific models will be built. First, the model will be created manually, then process automation will be introduced, which will allow the building of similar models in an automated fashion. This task also serves as verification of the selected method and simulation environment performances. Practical improvements for working gearboxes will be designed based on results from the stray current simulation.

1.3 Document Structure

This document is comprised of the following chapters:

Chapter 1 presents an introduction to the project and the document.

Chapter 2 presents the gearbox principles, based on torque density improvement.

Chapter 3 presents the flange connection manufacturing process, engineering principles and remanufacturing targets.

Chapter 4 provides a general problem description of stray currents and mitigation plan.

Chapter 5 summarizes results from demonstrators.

Chapter 6 reports on developments from demonstrators.

Chapter 7 elaborates on remanufacturing potential of flange connections and stray current resistance.

2 Gearbox principles based on torque density improvement

The high pressure to build lighter, more heavily loaded, more efficient and extremely reliable designs on lower cost defines the main requirements for a gearbox and drivetrain design.

- The key physical phenomenon defining main dimensions of the gearbox is the **input torque (kNm).** Torque density (Nm/kg) is used to define the quality of the design in the terms of material usage.
- Cost of a gearbox is dependent on the material amount and cost. The higher the torque density ratio is the less material is used to transmit the corresponding torque.
- The use of **torque density (Nm/kg)** can be expanded to provide guidance for the drivetrain system level architecture to lower turbine structural size and weight.

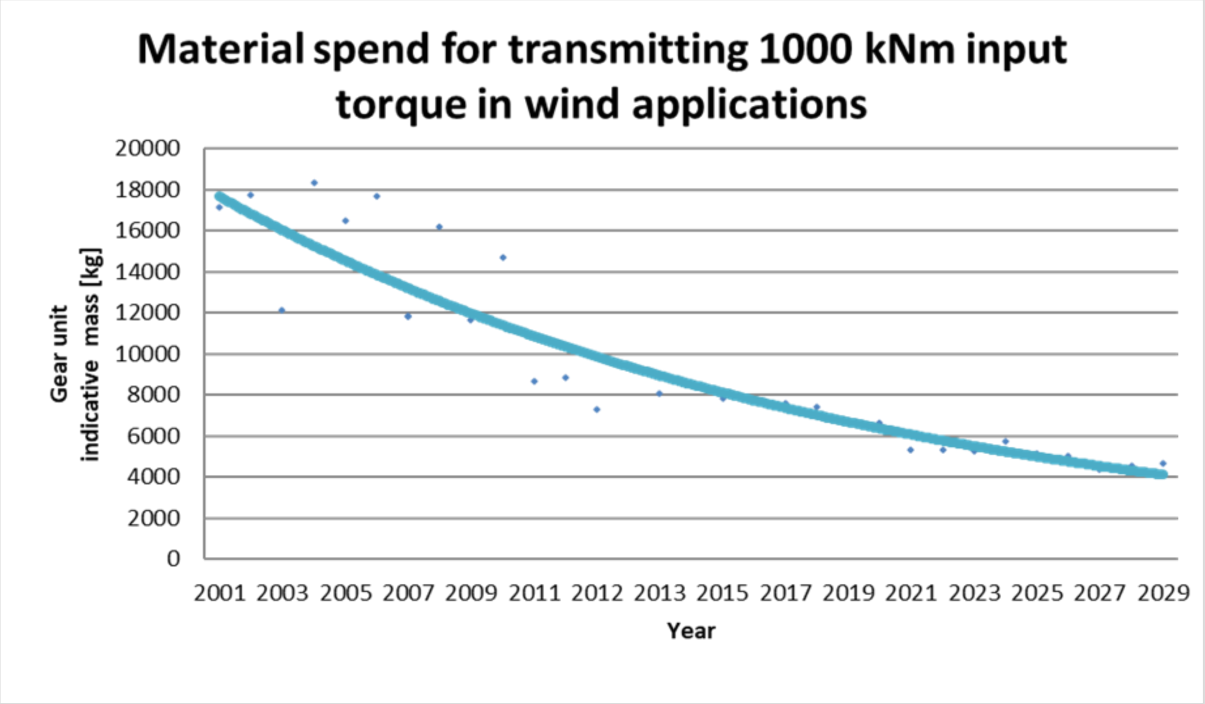

Figure 1: With increased torque density the material spends of wind turbine gearboxes is lowered significantly during the years.

Even with the high-quality standards in design work and workmanship, there are still premature failure cases, which are not fully in the design or monitoring scope of the current technologies. Partly these premature failures are explained by the fast implementation and growth of the new machines. Flange and ring wheel connections are one of the most problematic topics when gearbox dimensions have come smaller, but rotor torque has come bigger (see Figure 1). Connection between gearbox support to turbine frame and the ring gear (see Figure 2) can lead to local deformation and sliding in the interfaces. Improvements can be exploited to higher torque density.

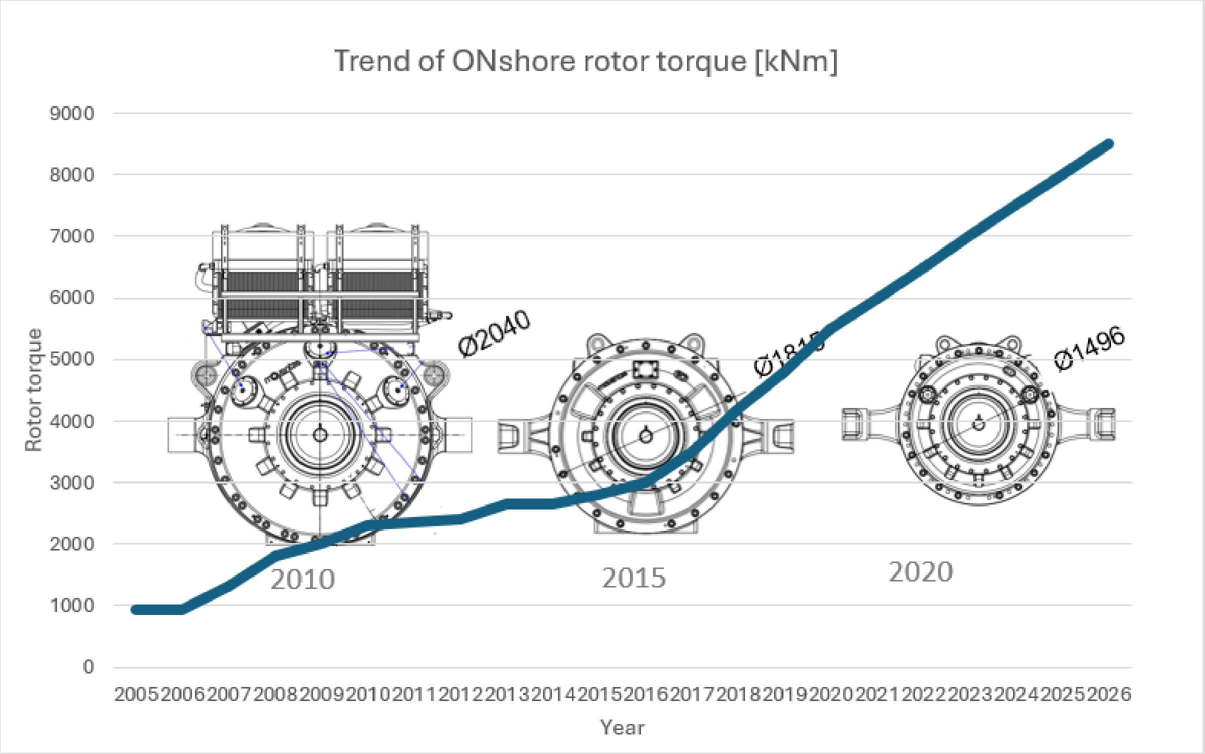

Figure 2: With increased input torque and torque density the diameter of the torque transmitting flange connection is decreased.

3 Flange connection in gearbox

Flange connection is a connection in gearbox planetary type stage between the ring and supporting structure, shown in Figure 3. Supporting structure located on the side of the wind turbine rotor is often used as a fixture to turbine frame as well, called torque arm. On the generator side there is a support structure connecting 1st and 2nd stage rings where there is another possible risk of micro movement. It is the rotor side surface which is considered limiting due to higher torque and risk of deformation, which can cause fretting corrosion. FEM visualization of the flange connection deformation can be seen in Figure 4. In the case of multiple planet stage gearbox, it is usually the 1st stage that is considered bottleneck.

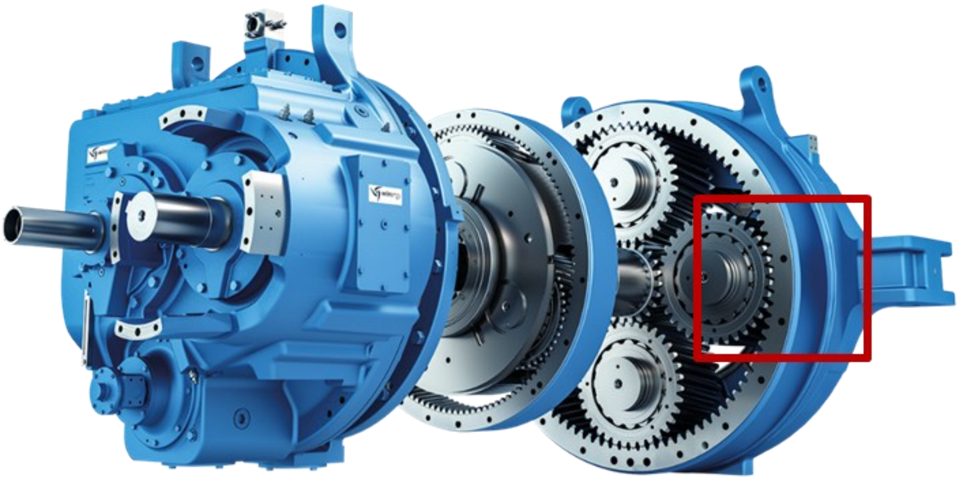

Figure 3: Rotor and gearbox torque is transmitted via bolted connection between the turbine frame and gear forces.

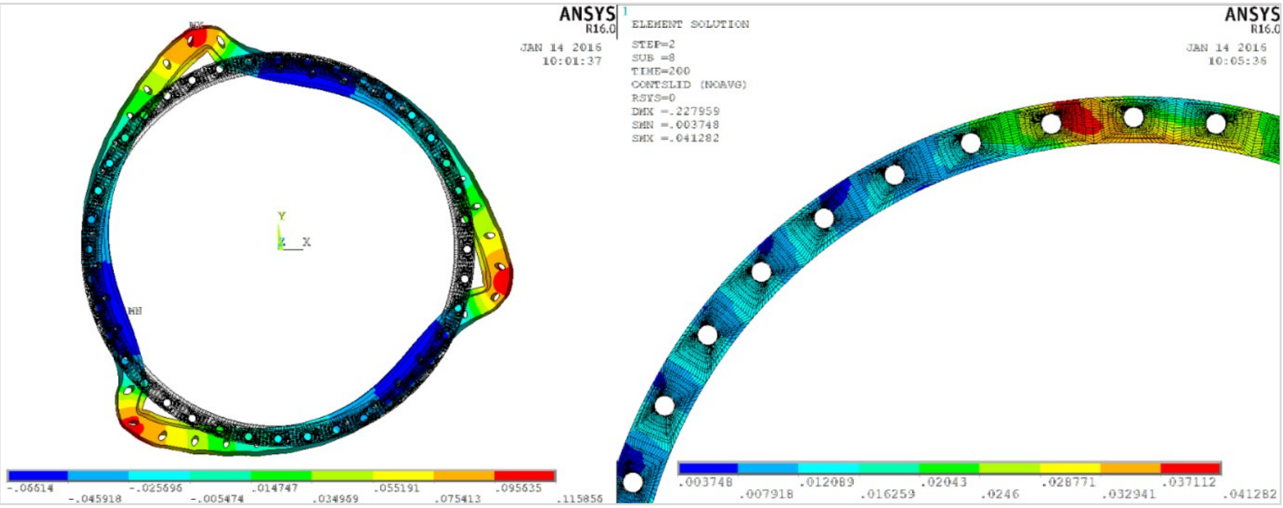

Figure 4: FEM results of the deformation of flange connection ring wheel.

3.1 Manufacturing process

As mentioned in the previous section, the flange connection consists of multiple parts and different materials which can and are used in different designs.

Ring gear usually is made of forged steel and can be heat-treated in multiple ways. Commonly used materials are alloyed quenched and tempering steels. These steels are usually delivered in quenched and tempered through hardened condition with requirements to mechanical properties according to either applicable standards or specifications specified in the order. These steels may be further surface hardened with methods like nitriding or induction hardening.

Supporting structures are usually castings made of either spheroidal graphite cast iron or lamellar cast iron. These can also be further heat-treated to increase the strength, and the connecting surfaces are machined according to specifications.

Bolt materials are usually made by standards to strength grades, such as 8.8 or 10.9. The amount needed as well as rim thickness i.e. area of the connecting surface is chosen based on FE analysis of the components.

3.2 Engineering principles

The flange connection is usually connected by bolts with different strengths, quantities and tightening procedures. In addition, calculation considers factors such as friction coefficient (surface roughness, material pair, tightening force) and tangential forces caused by planet stage causing local deformation and sliding. These forces can cause local wear, leading to fatigue failure.

Wind turbine gearboxes with higher torque densities require increased friction coefficients. Today the coefficient is 0,14, but in the future higher coefficients will be required, such as >0,3. Local forces of the ring gear to planet wheel contact lead to local deformation and sliding between the components. The amount of sliding, number of cycles, and local pressure can create wear, which can damage friction enhancers used in the flange connection.

Engineering requirements are guided by IEC 61400 standard, which refers to the best practices.

Housing split plane for gear removal or flange connections, shall be maintained oil tight. Typically, this is done by O-rings and sealing compound [REF-01].

Bolted housing joints between the annulus and mating housings in epicyclic gearboxes require special design considerations to avoid motion and fretting between the members. The joint shall be capable of carrying the maximum operating load by friction under the bolt tension. Solid pins are added to carry the extreme load. Pins and friction-based load carrying capacity are analysed separately. This means that the connection can be dimensioned with basic evaluation of pin shear and contact pressure evaluation and in other hand clamping force and friction-based evaluation of the bolted connections. There is no detailed method or requirements documented for the long-term fretting and wear analysis. In other words, the number of bolts and pins are selected purely by torque point of view and not to prevent fretting. During the time gearbox manufactures have gained the experience how to prevent fretting in some extension.

3.3 Remanufacturing targets

Failures due to unknown phenomena need new technologies for remanufacturing. To address this, the following targets are mentioned in the Grant Agreement of R3-Mydas:

i. increase the availability (energy production) of the existing wind turbine fleets to lower energy costs and stabilise production volumes;
ii. prevent premature failure cases – servicing operations are pricey and logistically complex;
iii. create validated repair methods.

This deliverable, focused on flange connections, will address (ii) prevention and (iii) repair. The target is to prevent failures through the use of state-of-the-art control of friction and create a concept for repair of flange components through additive manufacturing method.

4 Stray currents in gearboxes

Stray currents represent electrical currents that flow through mechanical components of the gearbox and are undesired, because they lead to electrical discharges in contact areas that cause damage to the contact surfaces. The sources of stray currents are mostly generators and electrical motors. High frequency switching in inverters and converters (e.g., IGBTs or MOSFETs) generates EMI, inducing stray currents in nearby conductive paths or grounded components. Parasitic capacitance between high-voltage components (e.g., motor windings, busbars) and the casing or other conductive surfaces can cause stray currents, particularly during rapid voltage changes (high dV/dt). As a design flaw, or due to corrosion improper or incomplete grounding of the powertrain components, can lead to potential differences, driving stray currents through unintended paths like the bearings or gear contacts. Pules Width Modulation (PWM) techniques used in motor control create high-frequency voltage transients, which can couple through parasitic capacitances or inductances, generating stray currents.

4.1 Stray currents modelling

Stray currents paths can be identified from gearbox model topology. Every metal-to-metal connection is a possible current path. Differences in resistance between parallel currents paths result in current sharing proportional to the conductance of the current path. Mechanical components in gearbox are lubricated using mineral oils, which are electrically isolative. This means that once the oil film is created between moving components, they are effectively separated from each other. However, the dielectric oil layer between conductive elements creates capacitance that can be charged by the potential differences. Once the charge reaches high enough level, a spark is created that breaks the isolative oil barrier and rapid discharge occurs. Such discharges lead to surface damage.

To understand how stray currents affect specific gearbox design, a detailed model is required that contains electrical characteristics of the gears, bearings, shafts, and case elements. In addition, a mechanical model is required to represent changing state of oil film, which acts as isolative layer. Loading and rotational speeds of the shafts are dynamic parameters that determine oil film thickness. In stationary condition, the oil is squeezed out from the contact zone and metal-to-metal contact is created, which allows electrical potential equalization. However, once torque is applied, the oil film can be created. This changes the electrical model parameters. Therefore, the electrical model parameters are based on dynamic mechanical model of the powertrain.

A gearbox contains gear contact pairs and bearings as main elements of stray current concern. The gear contact surfaces are changing as the gear pair rotates transmitting torque. Change in the surface affects the oil pressure in the contact zone and therefore oil film thickness. In case of roller or ball bearings rolling elements contact inner and outer raceways creating two contact pairs per each rolling element. Such contact pairs have capacitance and resistance, which is dependent on the oil film thickness, contact surface area, and oil parameters. The number of contact pairs is equal to the double number of rolling elements. In the case of journal bearings, there is only one contact pair per bearing, making their modelling simpler.

4.2 Stray current modelling results

Results of stray current modelling are time series of current flows through components and their interfaces. Additionally, the information about when oil isolative barrier is broken and spark occurs is available, which allows to draw conclusions on progression of damage accumulation over time. Current model works with ball and roller bearings as well as gear contacts.

4.3 Model validation and parametrization

The basic parameters required for the model are electrical and mechanical, as well as topology. Those parameters are estimated from experimental setup described in the following chapter. Similarly, validation of the simulation model is done by comparing its outputs to the measurements from demonstrator.

5 Demonstrators

In this chapter, results from demonstrators utilized in deliverable D4.2 are presented.

5.1 Gearbox demonstrator

A demonstrator gearbox was used to validate friction enhancers in the flange connection which is shown in Figure 3.

The test program was made to resemble customer wind turbine load case, with different kinds of loads. Load was increased in increments to see load behaviour, but with enough time for parts to allow run-in behaviour to occur.

To evaluate flange connection behaviour, a separate measuring setup was created to measure relative movement of flange connection with an inductive distance sensor.

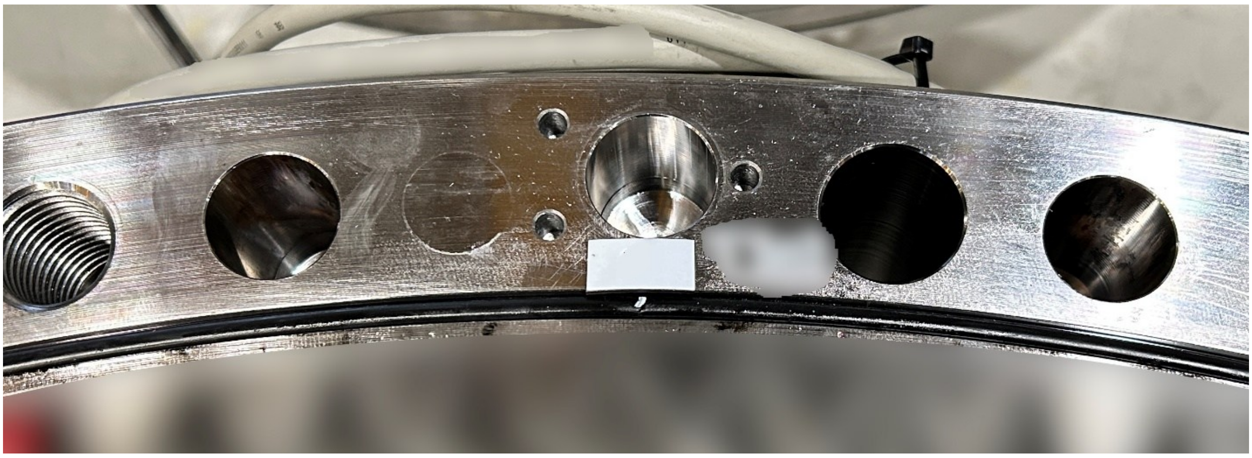

Figure 5: Condition of flange connection before tests.

Figure 6: Condition of flange connection after first test.

Figure 7: Condition of flange connection after second test, with friction improvements.

It can be seen from Figure 5 and Figure 6 that flange connection wear, i.e. fretting, has occurred. Different levels of fretting are visible on the flange connection in different locations.

In Figure 7, friction improvements have been implemented after the first test (Figure 6) without initial repair of the connection. This has allowed increased torque without similar increase in fretting. Friction connection surface is thus upgraded with friction enhancement without replacing the whole component.

Localized fretting was observed as seen in Figure 8. Fretting in this location is unexpected and may indicate that something is interfering with fretting behaviour and making it the weakest spot in the flange connection in relation to micromovement.

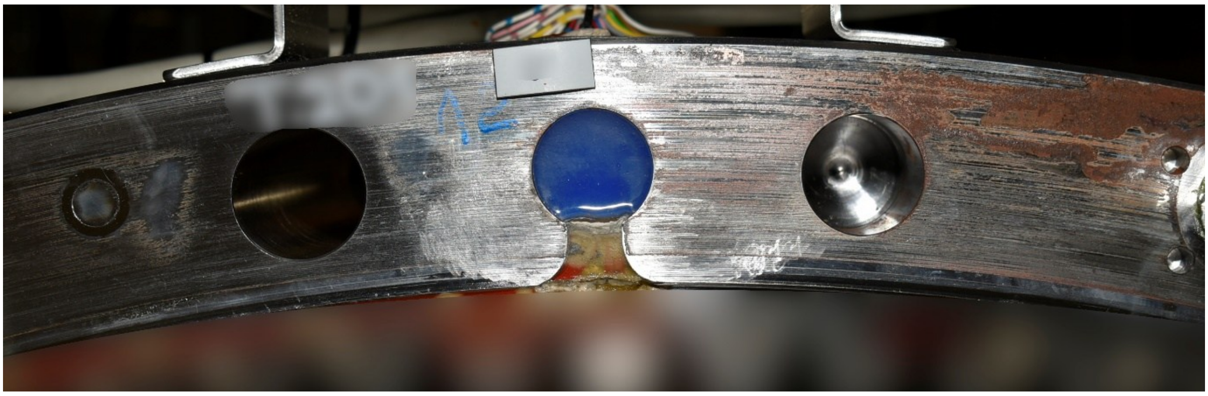

Figure 8: Example of localized fretting.

5.2 Stray current demonstrator

The stray current demonstrator (illustrated in Figure 9) is currently under development, therefore results are not yet available. In the figure below the design of the demonstrator is presented, which is under assembly.

The demonstrator aims to measure stray current flows through bearing and gear meshes to understand how they are affected by loading and rotational speed of the system. Different oils will be tested to find relation between oil viscosity, film thickness and isolation strength. Conditions at which electrical discharge occurs will be determined empirically to support computational model parametrization. Currently, the control and measurement system are being fitted into the demonstrator to allow its operation.

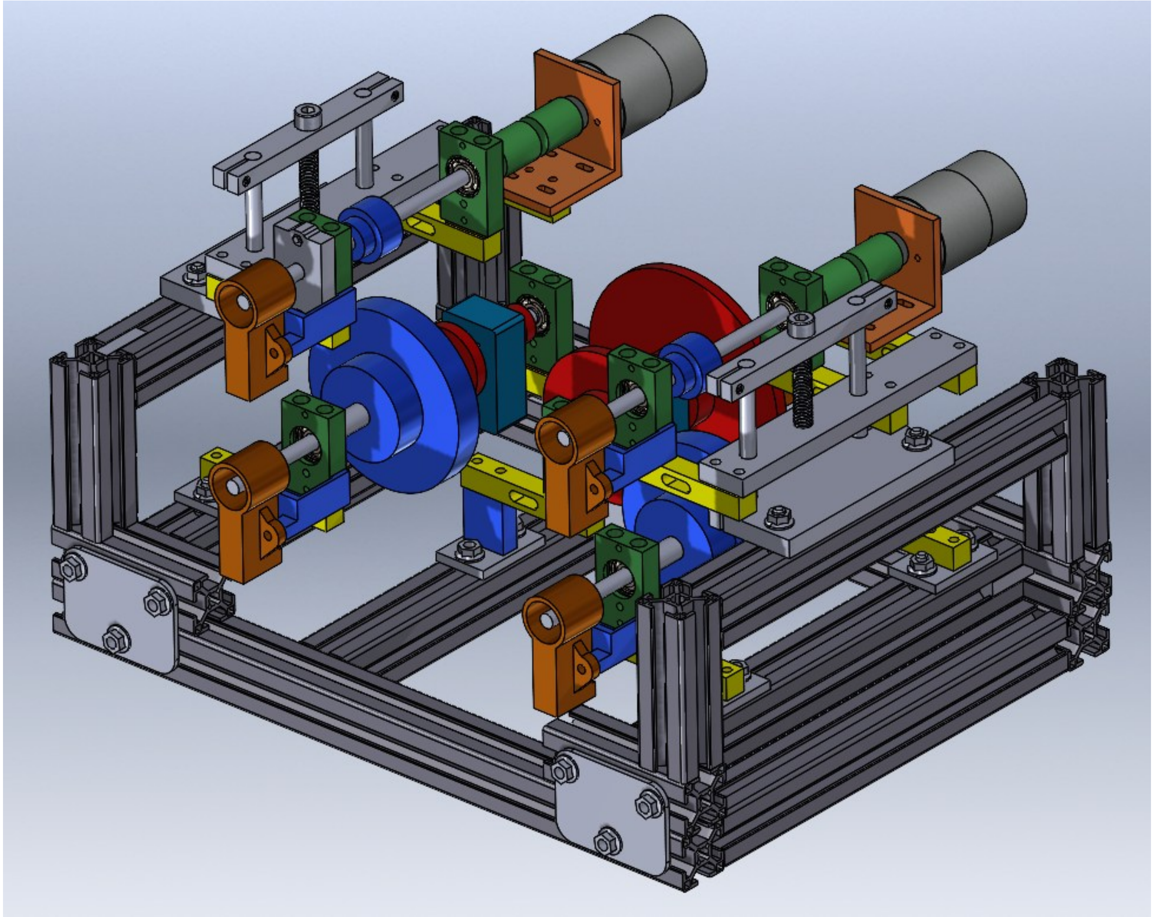

Figure 9: Small-scale gear and bearing tester.

6 Developments from demonstrators

Loads from the demonstrator will be used as reference load for specific flange tester being prepared. Localized fretting as seen in demonstrator gearbox will be considered in further demonstrator development.

The developed flange connection tester will be scaled down from demonstrator, with different setups of components and materials to be tested.

Stray current tester results will be used in B2B340 TFF tester and reported in deliverable D4.3.

7 Remanufacturing potential

Remanufacturing of wind turbine components has high potential related to generating jobs, reducing cost and lowering environmental impact such carbon emissions and utilization of steel materials. Especially now when the turbine market is not growing in Europe, companies will concentrate increasingly on after-sales activities. Since a lot of turbines have been built in Europe during the last two decades, the potential to repair or to replace wind turbine gearboxes is growing as a trend.

When wind turbine gearbox fails, it is required that the wind turbine operation be stopped, and the gearbox is lifted out from wind turbine for maintenance. This is a costly operation, in some cases calculated to be 10% or more of the overall turbine costs [REF-02]. After the gearbox is removed to service, one practice is to replace it with a new gearbox to ensure as fast continuation of operation as possible, but sometimes this is not possible, for example due to spare gearboxes being unavailable.

The first step for a gearbox that is arriving at service facility is the disassembly and inspection of the gearbox. An inspection report is made of inspected components and noticed failures are reported. This is done by service engineers through visual inspection. Based on the evaluation of the engineer, parts are either reused, repaired or replaced. In R3-Mydas remanufacturing is evaluated as an additional option (see Figure 10).

The remanufacturing value chain is shown in Figure 10 where in focus is on a component already in field, coming to repair. The options for the component as shown are: to be reused, manufacturing new component, buying new component or remanufacturing. Remanufacturing includes different types of repair methods as well.

Table 2 shows the business case for remanufacturing. The shown targets are for an example for repair of material locally and machining of material after.

Table 2: Remanufacturing business case and targets.

KPI name	***Abbreviation***	***Numerical target***	***Task related***
Reusage rate	*RE_rate*	*+98...99%*	*T4.2, T4.3, T4.4*
Prevention rate	*PRE_rate*	*-90%*	*T4.2, T4.3, T4.5*
Leadtime improvement	*LEAD_time*	*-75%*	*T4.2, T4.4*
Torgue density Nm/kg	*TD_*	*+5%*	*T4.2, T4.3*

Estimated cost for each option for flange component needing repair are as follows:

When reusing old component approximately 90% of cost and ~99% of energy can be saved compared to manufacturing new one. It can be estimated that component remanufacturing lowers cost ~60% and ~97% of energy consumption compared to novel manufacturing. Purchasing of new ring wheel will cause from 10 to 30% extra cost and consumes slightly more energy than internal manufacturing. Used ring wheels cannot typically be found from the markets.

It is challenging to evaluate remanufacturing of future products. In this project, 2 MW gearbox is used as a basis for evaluation. When remanufacturing 80% of rings, estimated saving annually in Flender Finland would be ~3700k€, which would secure jobs of ~200 employees in Europe. Annual savings in global scale and within next 10 years would be around 2200k€ per year. See Table 3.

Table 3: Remanufacturing business case vs alternatives.

Case: ring wheel for 2MW gearbox	Cost Range		
Method of sourcing	**Low (€)**	**High (€)**	**%**
Cost of manufacturing new ring	15000	20250	
Cost of reuse	1575	2363	-90
Cost of remanufacturing	6075	8363	-59.5
Purchasing new one	18750	25313	25
*) Cost of manufacturing is dependend on volume, geograpgics, required quality, price of energy... which might vary highly from one case to another. -> Cost range low and high are evaluated.			

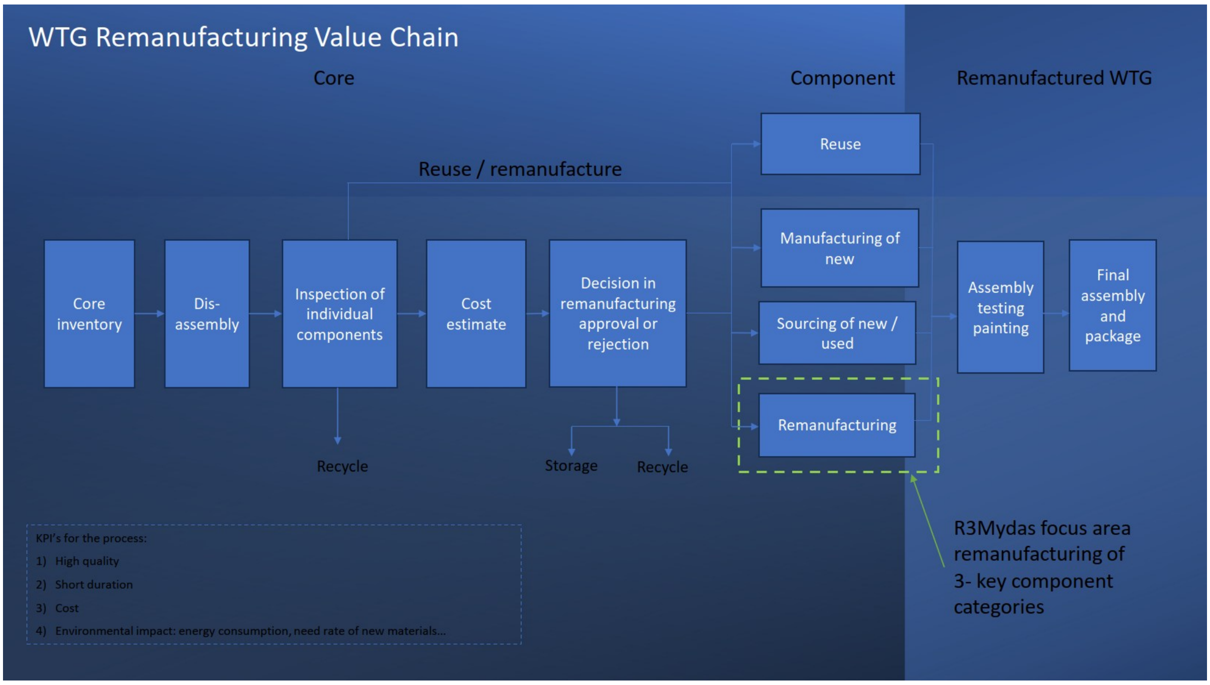

Figure 10: Remanufacturing value chain in wind turbine gearbox (WTG).

When 98% of ring wheels can be either reused or remanufactured, it will reduce related annual energy consumption approximately 98%. With the current Flender Finland typical volume, it means annual saving of 2000 MWh energy and 970 Tn of steel. When launched internationally to Flender group, saving would be approximately 3 times higher. It can also be estimated that annual business potential can double in the next 10 years because current typically larger (>2MW) gearboxes have 2-3 ring wheel instead of one.

7.1 Flange connections

Upgrade/repair of flange connection with friction treatment would follow the process:

1. Disassembly of planetary stage (part of other inspection in best case)
2. Friction improvements (cost)
3. Added lifetime and remove need for repair (potential saved costs)

Remanufacturing of flange would currently consist of following steps:

1. Removal of material from total surface
2. Laser cladding of full contact surface with same base material or material with similar air hardening (without need for follow-up heat treatment)
3. Machining of laser cladded surface

When saving 80% of ring wheels, annual material saving potential can be estimated as 790 000 kg in Finland and 1 600 000 kg in globally.

7.1.1 Visual inspection by machine learning

Flanges in service are inspected and evaluated by visual inspection, as mentioned in the previous sections. This is done manually by the service engineer writing the disassembly and inspection report. During the project, the possibility to utilize visual machine intelligence to evaluate component remanufacturing feasibility was investigated with CSEM. A workshop was organized by Flender to specify failure type for visual evaluation for CSEM to propose a solution. It was however determined that to implement visual inspection by machine learning a learning material of thousands of pictures would be needed. This was seen as unfeasible within the scope of the project.

Visual inspection by machine learning is seen technically feasible, but using reference pictures is seen too costly and too much effort for learning. If self-learning models can learn from support materials, these could be tested as an alternative method and evaluate the accuracy of the model.

7.2 Stray current resistance

Stray currents occurring in the system need to discharge to ground potential. Following the Kirchoff's law the currents will divide between possible current paths proportionally to the resistances of those paths. While in solid components, the resistance can be assumed constant throughout any operation conditions, mechanical connections, especially contacts are affected by contact pressures, relative motion speed, and properties of any intermediate conductors or isolators. In case of bearings, contact surfaced are separated by oil films, which are generally isolative barriers. However, oil film thickness is a function of load, rotational speed, clearance between parts, and oil parameters. Therefore, it is variable during different operational conditions, and so is the apparent resistance of the film. In stationary conditions, oil is squeezed out of the pressure zone allowing metal-to-metal contact leading to low-resistance current path. In operation, the oil film is created changing apparent resistance of the oil film to the range of megaohms, which practically means electrical isolation. However, the dynamic nature of the loading, can lead to a situation where oil film thickness is low enough in comparison to the voltage potential difference between metal interfaces where a spark can penetrate the oil film leading to voltage potential equalization. Such effect is destructive to the metal surfaces and undesirable. In this work package we aim to understand the conditions when stray current resistance is changing, factors that affect it and mitigation strategies for eliminating of the discharge in mechanical contacts.

8 References

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[REF-02]	Renewable Energy World, Wind Turbine Gearbox Reliability: Failure in Conventional Rotor Support Concepts, Web publication. URL: https://www.renewableenergyworld.com/wind-power/turbines-equipment/wind-turbine-gearbox-reliability/, accessed 2025-05-20	