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## A Systems Approach towards Reliability-Centred Maintenance (RCM) of Wind Turbines

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### Abstract

Wind turbines are a proven source of clean energy with wind power energy harvesting technologies supplying about 3% of global electricity consumption. However there is an increasing demand on maintenance and operational improvements since turbines have been plagued with downtime problems of major components e.g. gearboxes and generators, especially with offshore turbines which are difficult to access. Reliability Centric Maintenance (RCM) is a way of capturing the potential causes of downtime and poor performance by preventing failures and having a proactive approach to operations and maintenance (O&M). However, for a large fleet of turbines, adopting the RCM approach becomes difficult due to the complexities that arise as a result of the interactions between individual elements that make up the system in the product lifecycle. This paper discusses how a systems thinking approach can be used to identify the relevant aspects and possible interactions between the RCM approach and wind turbine gearboxes and also how the gaps that exist within the system can be closed so as to add value to business. The outcome of the paper is a proposal for applying a systems approach to wind turbine gearbox operation and maintenance, optimising the asset value adding contribution at minimal total cost to the operator.

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### 1. Introduction

The wind industry within three decades has come a long way, with wind turbines now being a proven source of clean energy producing about 3% of the electricity consumed globally [1]. Consequently, the requirements and expectations of wind turbines keep increasing. Fulfilling the increasing demand, wind turbines have become larger generating more power for consumers, but still are expected to perform their required duty without interruption for the most part of their in-service lifecycle. However there is an increasing demand on maintenance and operational

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improvements since turbines have been plagued with downtime problems of major components e.g. gearboxes and generators, especially with offshore turbines which are difficult to access. With the annual installed capacity growth rate slowing down due to the global economic crisis [2], the service business is now a means at which wind turbine manufacturers can remain profitable. A recent article on Bloomberg [3] indicates that there is now a shift from manufacturing towards the service business, in which the service business of Vestas Wind Systems A/S, the leader in the wind industry, grew at an annual rate of 25% during 2011. This is because about 96% of all turbines sold by Vestas are on some form of service agreement.

In the wind turbine industry, it is not uncommon to see many of the wind park projects having some form of operation and service agreement or warranty structure between the wind turbine manufacturer and the customer. These agreements may run for 2-3 years or up to 10 years or more (for a full service agreement). Vestas has what they call the Active Output Maintenance® service programme (AOM)<sup>†</sup>, which has 5 stages depending on the level of turbine services the customer is willing to pay for during the life time of the turbine. With the risk involved in the business, the majority of wind farm owners/operators sign full agreements with turbine manufacturers. It is then the responsibility of wind turbine manufacturers to ensure that the turbine is monitored continuously and is always available. Once there is a fault, they are also responsible for the maintenance and repair. This is a double-edged sword as turbine manufacturers incur costs for downtime of a failed turbine but also the knowledge derived from continuous monitoring and maintenance of the systems, can and should help turbine manufacturers improve the quality and reduce costs of their products and services.

Reliability-Centred Maintenance (RCM) which many industries have used historically to tackle similar challenges in service industry [4, 5] is now finding its way towards wind applications [6, 7, 8]. Compared to the aircraft, nuclear and many other industries, the wind industry is relatively young and has had only about 30 years to work towards getting to the status which took industries like aircraft and automotive about a century to achieve. Hence, the successful application of RCM in the wind sector might be flawed if there is not a full understanding of the impacts and contributions the various elements of the system to delivering an effective RCM programme. In this paper, the authors look at the main RCM tools and techniques and how systems thinking can be applied to effectively use the tools optimally without affecting the performance of the overall system. A focus will be directed more on the interactions between the major elements and not on the specific description of how to apply RCM tools. However, a brief and taxonomic literature review on RCM and its applications in wind and other industries will be presented to give an overview of the methodology.

## 2. Reliability-Centred Maintenance

According to SKF Reliability Systems [9] RCM is:

*“an approach that employs reactive, preventive, and proactive maintenance practices and strategies in an integrated manner to increase the probability that a machine or component will function in the required manner over its design lifecycle with minimum maintenance”.*

RCM which started in the aircraft industry, and later within the military, nuclear and oil & gas industries, provides a framework that utilises operating experience in a more systemic way [4]. The goal of RCM is to preserve the most important equipment (system) function with the required reliability and availability at the lowest cost of maintenance [4, 9]. Most authors, including Selvik and Aven [5], agree that as well as reducing maintenance costs, RCM also increases safety and reliability. However, Rausand [4] suggests that RCM cannot improve reliability of a system but only ensure that the inherent reliability is realized. He went further by arguing that reliability can only be improved through redesign or modification.

This paper looks to examine the links between the main stages of the RCM technique and other aspects of the product lifecycle including feedback to the design phase, hence building on Rausand's argument [4]. This paper aims to take the RCM technique further from just the functional failure analysis and optimization of maintenance strategies by looking more holistically through the application of systems thinking tools & techniques. The authors do not wish make an indepth study of the specific analysis of the most relevant functional system failures and Preventive Maintenance (PM) optimisation techniques of wind turbines, but choose instead to look into how the

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<sup>†</sup> <http://www.vestas.com/en/wind-power-plants/operation-and-service/service.aspx#vestas-univers>

interacting elements of RCM can be manipulated towards achieving the desire of maximising the asset value adding contribution (focused on improved reliability) at a minimal total cost reduction through applying systems thinking.

The authors also argue that a good implementation of RCM should be fully integrated with other interacting elements in the product lifecycle. This implies that there should be some explicit linkage of RCM to other processes such as design, manufacturing, validation and quality management. The wind industry is now cost driven which implies that RCM should optimally satisfy both cost and reliability objectives.

### 2.1. RCM Framework

Rausand [4] presents a structured approach to RCM using a sequence of twelve activities and steps which Selvik and Aven [5] summarised into a two step procedure:

- i. Inductive analysis of potential failures, where a failure mode, effects and criticality analysis (FMECA) is used to determine critical components of the system.
- ii. Application of logical decision diagrams to specify suitable categories of predictive maintenance (PM), replacement, etc.

There have also been several improvements to the traditional RCM methodology for different applications, e.g. RCM 2 [10], Reliability and Risk Centred Maintenance (RRCM) [5], Streamlined RCM [11], Reliability Centred Asset Maintenance [12, 8] and the SRCM methodology [9]. Although the detailed procedures of the various forms of RCM listed above are different, the main ideas of RCM presented in each source are more or less the same. Fig 1 shows how interpretations from Rausand [4], Selvik and Aven [5] and Fisher *et. al.* [7], can be used to summarise the main steps of the RCM methodology.

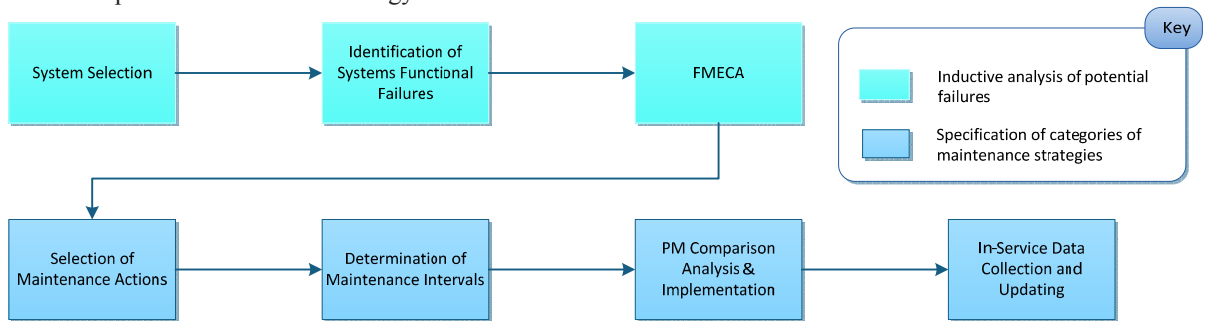


Fig 1 RCM Stages [4, 5, 7]

A typical wind turbine consists of a Rotor (which carries the blades), Nacelle and a Tower. The major components (Drive Train and Generator) are contained in the Nacelle. Literature has shown that gearbox failure and downtime are one of the major causes of poor wind turbine reliability [13, 6]. Also Fischer *et. al.* [6] suggested the gearbox to be the most critical sub-system of the wind turbine after analysing the failure frequencies and downtime of all major sub-systems of the wind turbine. The authors agree with Fischer *et. al.* [6] and add that not only because the effect of failure frequencies and subsequent downtime are gearboxes very critical but also because of the relatively high costs attributed to downtime mobilisation, logistics and replacement of gearboxes. This is also emphasised by Musial *et. al.* [13]. Therefore the direction of this study will focus on the wind turbine gearbox when examining the various relationships between RCM and the overall lifecycle of a wind turbine. Furthermore, from the product lifecycle management (PLM) perspective, a product<sup>‡</sup> is described by the stages it passes through in its lifetime from its ‘conception’ as an idea up to its ‘end of life’ or decommissioning. Fig 2 below elaborates on the different stages of a product’s life from its design, through its production, use and disposal. The iterative feedback loops represent the continuous knowledge accumulation feedback process for improving each stage of the lifecycle. RCM is usually implemented during the operational stage of the lifecycle when the product is being used. However, RCM can also be planned for during the design and other early stages of the lifecycle.

<sup>‡</sup> In the context of this study product refers to the wind turbine gearbox

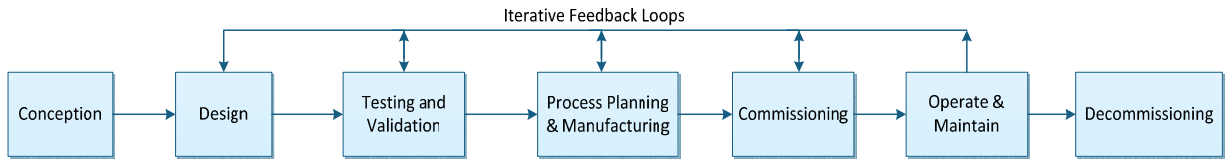


Fig 2 Product lifecycle diagram as described in [14]

The importance of integrating RCM with design through continuous iterative knowledge feedback will be explored further in the following section.

### 3. Systems perspective towards RCM

In systems thinking, the effects or outputs of any system are dependent on the interaction of its parts and studying the parts in isolation will not provide an accurate picture of the system [15]. A systems thinking approach helps to interpret real world problems and situations by looking at the bigger picture and clearly identifying the boundaries and levels of interaction between constituent parts of a system and also between several systems. Literature shows that all systems can be defined by common characteristics [16]. Such characteristics include: 1) system-environment boundary, 2) input, 3) output, 4) process, 5) state, 6) hierarchy, 7) goal-directedness, and 8) information [17]. Fig 3 for example, shows a summary of the inputs, outputs, controls and enablers (IOCE) context diagram for the wind turbine gearbox RCM framework. This diagram begins formulating the problem in a way that will help to find a better understanding of the interacting elements of the RCM framework and other systems.

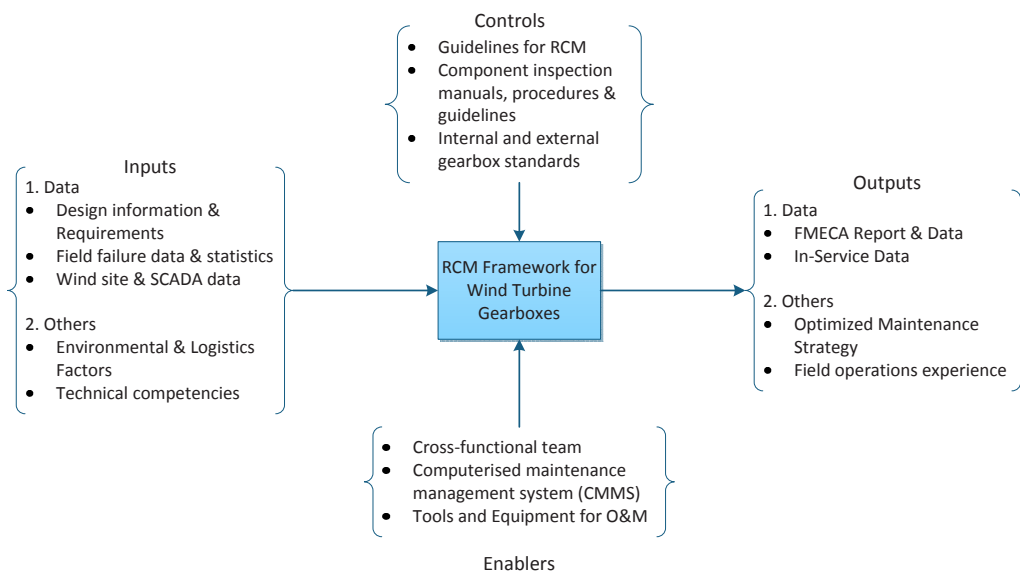


Fig 3 RCM framework context diagram

#### 3.1. RCM and the product lifecycle

From Fig 3 it can be seen that the constituents of the IOCE for the RCM framework make up the other stages in the product lifecycle. Using the context diagram and the product lifecycle (Fig 3 & Fig 2) as a guide, a SIPOC (suppliers, inputs, process, outputs and customers) diagram [18] (see Fig 4) can be made for the RCM framework to clearly understand the specific links of RCM framework for a wind turbine gearbox to other stages of the gearbox lifecycle. Suppliers and customers define the cross-functional teams and individuals who are stakeholders in providing the inputs and making use of the outputs respectively, from the RCM framework. For the purpose of this

example, the majority of suppliers and customers are internal to the organisation, with the only external stakeholder being the gearbox manufacturer. The inputs to the process considered here are mainly the data which are required for RCM. This data varies from design to field data and requires individuals with respective technical competencies to make use of them for RCM. Also, the suppliers and customers of the RCM process are mostly the same groups of individuals, however, they make use of different inputs and outputs of the process. For example, the design engineering team are responsible for providing design information which are needed for RCM, however, they also have to make use of other data like failure and repair information for design reviews. Hence for an ideal RCM framework to be implemented, these stakeholders will have to participate in shaping the requirements for the process directly or indirectly. For example, design & manufacturing data are needed to be correlated with field operations data in order to identify the functional failures and select critical components. Therefore, the RCM group working on these aspects should be made up of representatives with the knowhow of the design and manufacturing details of the gearbox as well as those with field O&M experience.

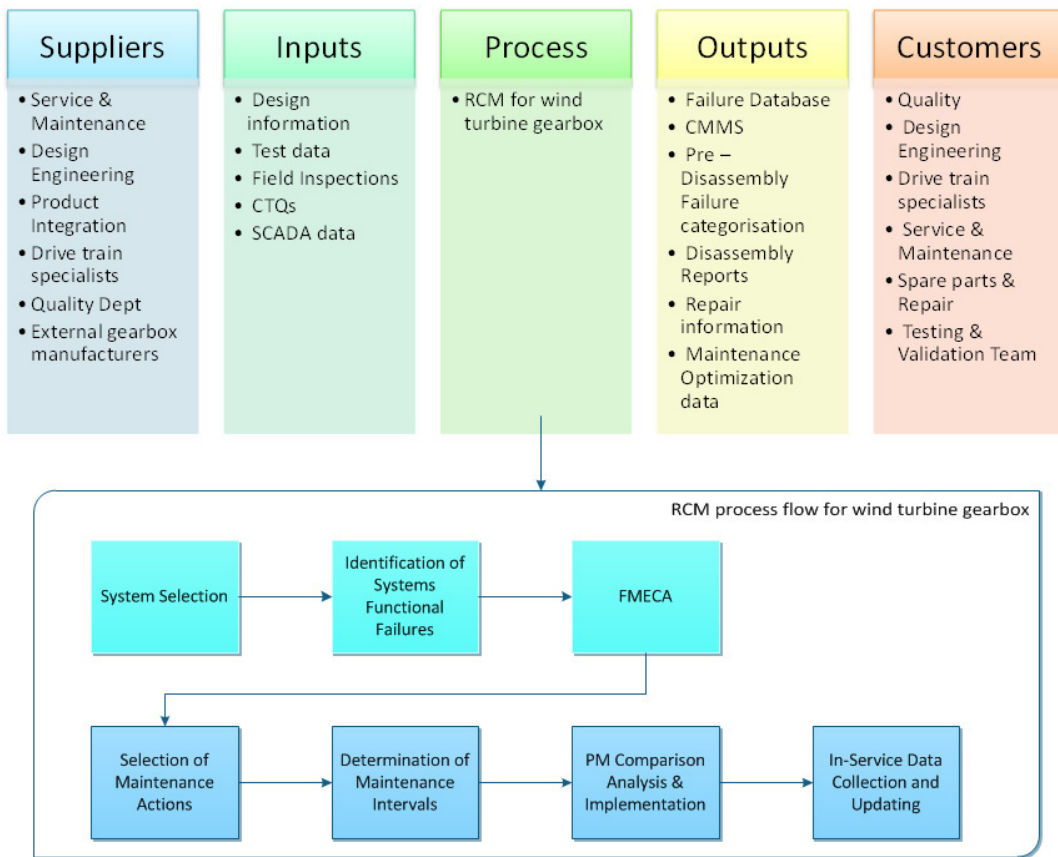


Fig 4 SIPOC for the RCM framework for wind turbine gearbox

### 3.2. The Lifecycle System of Systems (SoS)

So far, there has been a gradual build-up in describing and linking RCM to the overall product lifecycle. In the context of a wind turbine project, the systems representation of the lifecycle is shown in Fig 5 below. The two clouds represent the production (in blue) and services/operations (in green) stages of the lifecycle showing the important interactions between major constituents of both systems. In a quick run through, a gearbox after being designed will go through a series of tests and then once manufactured will have to be integrated with other sub-systems of the wind turbine (product integration). After integration with other components, the turbine is then installed in the field (construction) after which the service and operations lifetime begin in the field. The field

operation is characterized by plant operations and platform management. Plant operations are responsible for running individual wind farms while the platform management consists of those responsible for managing specific wind turbine type across different regions. Both the plant operations and platform management are responsible for overseeing service and maintenance of the turbines. The diagram also shows the connecting links from design to the field O&M stages and also the links between the quality team and other upstream stages of the lifecycle. Finally, the top management oversees all the different stages emphasizing the importance of aligning all stages of the lifecycle to the overall business strategy.

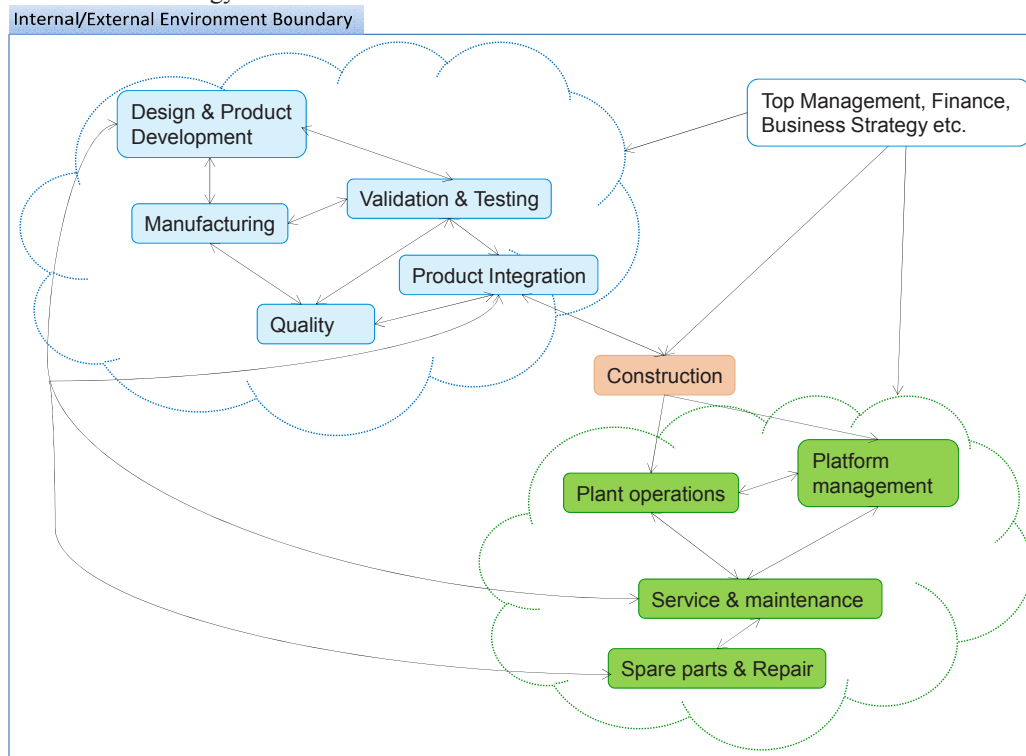


Fig 5 Systems diagram representing the key stages of the lifecycle of a wind turbine gearbox

## 4. Discussion

The previous two sections have presented the RCM framework for wind turbine gearbox maintenance and applied systems thinking to understand how the various stages of such a framework interact with other stages of the product lifecycle. This section will discuss further these interactions by looking at three key stages where the RCM framework can be anchored to the overall lifecycle.

### 4.1. Data collection and analysis as a vital input for RCM

During operation the gearbox is subjected to varying loads depending on the site conditions the wind turbine is exposed to. Typically, data is needed for the functional failure analysis, some of which have been identified in the previous section (see Fig 3). However, Fig 6 below shows the component lifecycle of a gearbox and its sub components, indicating the various types of data within the entire lifecycle. Data required for RCM analysis spans across the lifecycle but the data collected during RCM is limited in scope. Hence there is a need to clearly map out and identify the potential sources of data and align them to RCM so that the right analysis can be carried out. On the other hand FMECA should identify possible gaps in some upstream processes (e.g. problem with manufacturing process due to error in a batch production). This can be realised through a good correlation of field failures with

operation data to make accurate judgements about the functional failures through a root cause analysis (RCA) that reveals this.

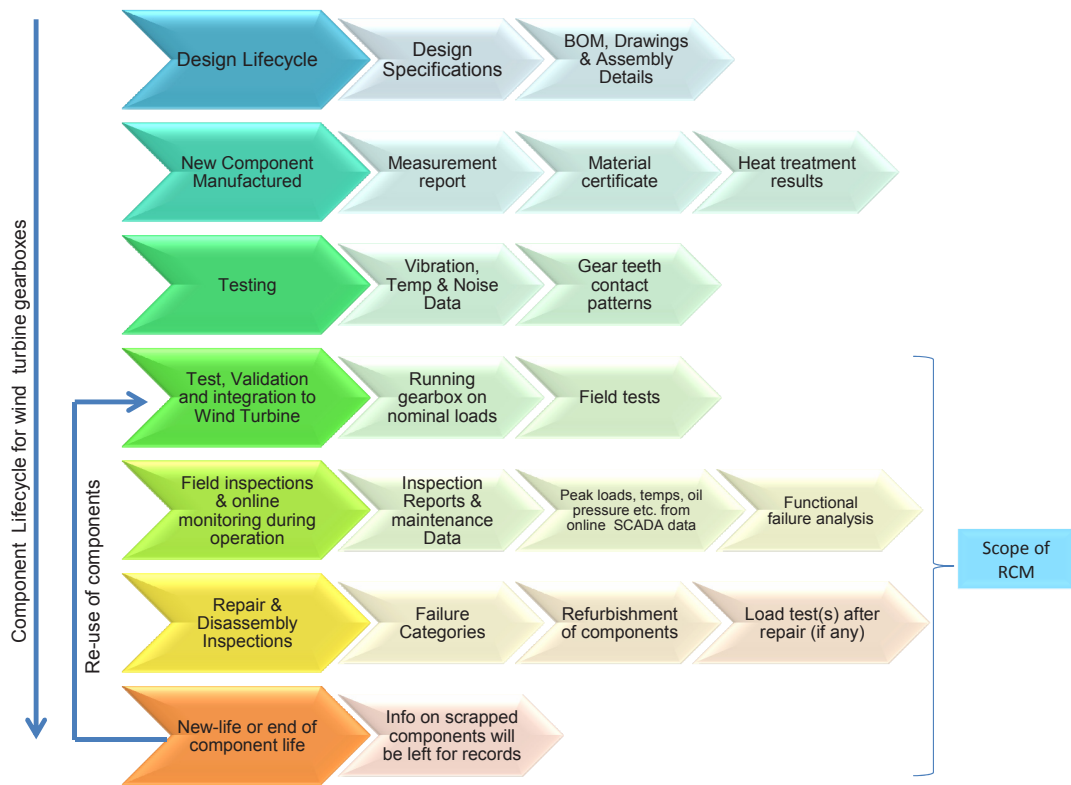


Fig 6 The lifecycle of a geared component showing key stages of engineering data collection/usage

Finally, when collecting and documenting data during FMECA and field inspections, the data collection template should have similar terminologies used by design engineers for classifying gearbox failure, wear and tear. This will help for an easy correlation of field failure statistics to design requirements and identify the critical to quality (CTQs) failures.

#### 4.2. Implementing RCM

Once the critical failure modes have been identified, a maintenance strategy can be selected based on logical RCM decision tree [7, 6, 9] and probabilistic models for maintenance optimisation [5]. RCM optimises the various maintenance strategies based on the findings from the functional failure analysis. For gearboxes, planning and implementing a PM programme under the RCM approach can be complicated due to the variety of gearbox designs installed in turbines under different operating conditions. A key focus area when implementing RCM is that inspection manuals and procedures should be designed and prepared by a technical team with both field and design experience. This on the one hand, will help the design engineers to ensure that the service technicians' tasks are aligned to design guidelines so that after a series of maintenance tasks or inspections, the results will be easily correlated to the design information. While on the other hand, those with field experience will ensure that the technical guidelines can be interpreted into a language the service technicians understand. Another key area where a good link between the O&M activities and design is needed is in assessing the design for maintainability of major systems. In the case of a wind turbine gearbox the question RCM points out in the design phase is how easy it is to disassemble, gain access to major components and then assemble especially when repairs are to be done inside the turbine (up-tower). In current gearbox designs, the capability of up-tower repairs is limited not only due to the lack of competency or tools but due to the difficulty in accessing and disassembling major components. Future Gearbox

designs are now seeing modifications which will allow such repairs especially for offshore applications [8]. This now calls for a more holistic view to the design of wind turbine gearboxes (and other components) where the serviceability and operation life is taken into account during the design. It can be argued that since the wind industry is still relatively young, it has had to learn from its experience in order to make such improvements in design. The authors emphasise that, the way forward would be for more close integration of the field O&M activities to up-stream design through adequate feedback for redesign and improvements (this is discussed further in the next section).

Introducing more up-tower repairs into the RCM of wind turbines will have tremendous cost savings. This is because a large portion of the cost to replace (repair) the main gearbox components down-tower is attributed to transport and logistics. These include the crane for taking down the gearbox from the turbine, as well as the cost for shipping and transportation. In offshore applications, these costs become astronomical due to the difficulty in accessing the turbines and more expensive modes of transport e.g. barges, vessels & helicopters for technicians. Being able to replace major components on site (up-tower) will remove all the costs attributed to transport & logistics. In this case, the only cost accrued during repair will be the spare parts, technician transport and labour costs.

#### *4.3. Feedback of RCM to design for continuous improvement*

The question that arises after RCM has been implemented is: “does it end here?” The answer is no. Rausand [4] noted that the full benefit of RCM is only realised when O&M experience is fed back into the analysis process. Implementation of RCM also includes design changes [9]. The issue of appropriate feedback of RCM to design has not been emphasised in the main literature on wind turbine RCM applications. This is because previous works largely focus on functional failure analysis and maintenance optimisation rather than the contribution towards improving reliability through prompting for redesign. The authors of this paper argue that even though an optimized RCM will not immediately improve the quality and other design properties of the product, good alignment and feedback of RCM implementation in the field to design will definitely lead to product improvements through the use of real experience data to bring about design modifications and redesign. This can be achieved by identifying the right CTQs during the field and repair inspections which will give an idea of what design features are critical to the performance of the system, thus helping to improve the redesign process. Being able to correlate operating conditions and design parameters to field failures is where every wind turbine manufacturer aspires to be. However, one step to achieving this is by having a good feedback from RCM to design.

Good feedback to design can be achieved through correct documentation and reporting of all field O&M activities, especially those that have to do with RCM. This can be achieved if a computerised maintenance management system (CMMS) is used, where all failures, safety incidents and maintenance tasks are recorded in detail up to the sub-component level. Moreover, the CMMS should be fully integrated with the other databases of the lifecycle in one central engineering database (see Fig 7 below). As presented in the SIPOC diagram, there exist certain connections between the key databases that make up the engineering database. As the lifecycle transfers from the design up to field maintenance, it is easy to obtain the right data that can contribute to a more effective deployment of each stage in the lifecycle, be it needing design information for field O&M optimisation or making use of real field data for redesign.

Many Industries already have some form of database where field O&M and failure data are recorded. A good example is the Offshore Reliability Data (OREDA) [19] for the oil & gas industry established in the 1980s, in which several companies record their safety, reliability and maintenance data in a unified and specialised way. In the wind industry some notable sources of failure data include: WindStats newsletter [20], WMEP [21], and EPRI [22]. However these are not good enough for detailed feedback for redesign since the failures recorded here are only major sub-system failures i.e. failures of the main-shaft/bearing, gearbox, control system etc. and not of specific sub-component level damage. Hence it is difficult to accurately analyse the component reliabilities and their contributions to overall reliability which can be done if the functional failures of the critical components are known.

Attempts to create a database for wind turbine gearbox component failures have already begun by the gearbox reliability collaborative (GRC) [23]. This will however depend on how much information turbine operators & manufacturers are willing to share. An alternative is to have an internal failure database (Fig 7), where each major turbine manufacturer can keep track of its field O&M as it would do for its design and manufacturing.



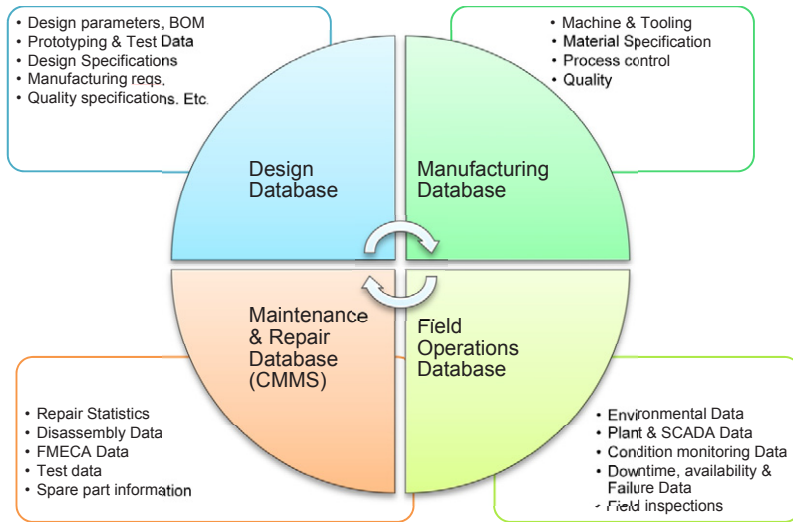


Fig 7 Central Engineering Database for PLM

**5. Conclusion**

The concept of RCM is well known in many industries, with the wind industry also embracing this technique. This paper applied systems thinking to understand how the interactions and interfaces between RCM and other stages of the product lifecycle can have an overall effect on fulfilling the RCM objectives (improved reliability and cost savings). Also, the authors have been able to identify the important links that exist between a RCM programme and other management systems especially aligning to the business strategy. These findings can be summarised, using the plan-do-check-act cycle [18] into a more generic framework applicable to asset driven industries.

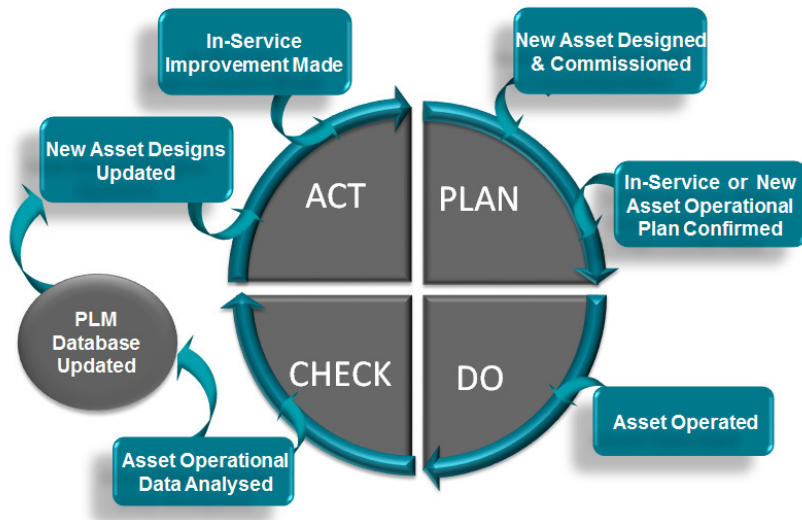


Fig 8 Framework for Holistic Lifecycle approach to RCM for Assets

This knowledge accumulation cycle follows the product lifecycle framework. It can be applied to in-service assets and the design of new systems. Of relevance to the key areas in which RCM is anchored to the lifecycle in this cycle are:

- Updating the PLM database with analysed asset operational data (which encapsulates the scope of RCM).

- Update of asset designs through proper redesign (only achievable through proper feedback from RCM).
- Implementing the changes through improved in-service solutions for assets.

Limitations with the proposed model focus around the usability. Perhaps the model is only suitable to those manufacturers who design, operate and maintain their own products or those operators who keep a close working relationship with their suppliers. However, those manufacturers who do choose to feedback in-service data to new designs will have competitive advantage over those who do not as over time their product reliability improves at a higher level with no extra cost. Future research should look to test the proposed model validating the usefulness, perhaps firstly operationalizing the concepts within the asset management of wind turbines and then testing the model in other asset management environments.

## Acknowledgements

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