IEA Wind Task 43
An Investigation of the Standards Landscape in the Wind Energy Sector

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Abstract

More can be done to develop digitalisation capability and enhance the value of generation assets within the wind energy sector. This includes building on developments already in place as well as taking advantage of advances in other industries.

This paper outlines the findings of an IEA Wind Task 43 sub-group which investigated the degree to which the availability of industry standards and guidelines support those activities and disciplines and contribute to higher asset value. A framework for assessing the coverage of standards and guidelines is presented along with findings from a preliminary gap analysis indicating potential areas for improvement.

Specific examples, or use cases, are presented which highlight the need for more effective development and deployment of standards or guidelines. In addition, a possible approach is proposed which could improve the “FAIR” characteristics of standards and guidelines i.e. rendering them more Findable, Accessible, Interoperable and Reusable.

Finally, suggestions and recommendations for further work are provided to enhance the availability of standards in support of wind industry digitalisation.

List of abbreviations

DIN	German standard / German institute for standardization
DNV	Det Norske Veritas; Testing, Certification and Technical Advisory Body (Norway)
EN	European standard
EPRI	Electric Power Research Institute (USA)
FAIR	Findability, Accessibility, Interoperability, and Reuse
FGW	Federation of Wind and other Decentralised Energies (Germany)
GADS	Generating Availability Data System (by NERC)
GSP	Global Service Protocol (by FGW)
IEC	International Electrotechnical Commission
IRPWIND	European Integrated Programme on Wind Energy Research
ISO	International Standardization Organization
KPI	Key Performance Indicator
LPS	Lightning Protection System
NERC	North American Electric Reliability Corporation
O&M	Operation and Maintenance
PDF	Portable Document Format
RAMS	Reliability, Availability, Maintainability, Safety
RDS-PP	Reference Designation System for Power Plants (by vgbe)
RDS-PS	Reference Designation System for Power Systems (ISO/IEC 81346-10:2022)
SCADA	Supervisory Control and Data Acquisition
vgbe	vgbe energy; International Technical Association for the Generation and Storage of Electricity and Heat
WindIO	Frameworks defining the inputs and outputs for systems engineering MDAO of wind turbine and plants
ZEUS	State-Event-Cause Code for Power Generating Units (by FGW)

Introduction

Wind energy asset owners wishing to maximize return on project investment are aware that asset value is directly related to the availability of objective information around performance, reliability, maintenance history, and other asset health indicators. However, given the diversity of sources ranging from machine data at component and portfolio level, to operational data reflecting processes and management practices, there are significant challenges in developing a comprehensive data-driven solution. Additionally, wind generation assets are complex systems made up of structural, electro-mechanical, and aerodynamically torque-driven components in a stochastic environment which adds to the challenge of managing and improving return on investment.

[Clifton 2023] found that the absence of good quality data is one of three major challenges in companies' endeavors in adopting new digital methods. Governance through standards and guidelines will help generate, curate, and better utilize data.

However, while the adoption of appropriate standards and guidelines is a significant factor in enabling interoperability and data sharing, it is challenging to navigate the spectrum of potentially relevant tools. Digital artifacts, standards documentation, databases, and legacy software codes can present challenges for the ordinary analyst. This project focuses on Investigating and alleviating these challenges, and applying FAIR practices to standards.

This whitepaper investigates the discovery, or findability, of existing standards not only in the wind industry but also considers potentially applicable standards from other industries. It highlights examples of gaps and the potential to close them with suggestions from other industries. A use case-based methodology is employed to help navigate the standards space and consider the data that could be collected from various product life cycle stages and processed along the data value chain stages [Barber 2023].

The following sections detail the approach and its application to selected use cases. Possible further work is highlighted which would help alleviate some of the issues identified.

Section *Standards Landscape Mapping Exercise* describes an exercise of scanning through the vast number of standards publicly available and obviously related to digitalization. To identify possible gaps within all those standards, the group categorized them by the keywords presented by the publishing organization together with the standards' description.

In the section *Framework for More Detailed Use Case Evaluation* the group did the next step of ordering standards by their contents and developed a two dimensional spectrum with the axes "life cycle stages" and "data value chain stages".

The section *Detailed Investigation of Specific Use Cases* provides descriptions of two different use cases. Work in these use cases struggles much with data handling or data wrangling respectively and could benefit much from improvements towards digitization and digitalization.

The *Conclusions* section summarizes the results. In the outlook we describe the idea of an ecosystem applying the FAIR principle for standards which would facilitate an easier search of a large database for appropriate standards. Containing standards and keywords and possibly more information, such a database could present graphical relationships between standards and contents in an easy to understand and navigable manner.

Standards Landscape Mapping Exercise

IEA Wind Task 43 on the Digitalisation of Wind Energy explored the major aspects of digitalisation to understand the challenges in deploying processes and solutions to help derive maximum value from various data sources. As part of these activities, a sub-team undertook an exercise to explore the availability of standards applicable to wind energy digitalisation use cases and, more specifically, those which might be relevant in maximizing asset value.

A major challenge, even with this bounded search objective, is the extensive range of individual wind energy use cases, each of which may map to a different selection of standards. The search space is further expanded when considering standards in other industry sectors in order to highlight gaps which may not otherwise be apparent**.** Furthermore, it is noted that there is neither a search engine nor a database, on a global scale, which could facilitate such an exploration.

Approach

To provide structure to the investigation, the team defined a two-dimensional framework within which to assess the availability of standards. The following high-level categories were chosen as representative of the major data or digitalisation use case value-chain stages.

On the horizontal axes, Data/Use Case Value Chain Categories are shown:
- Data Collection and Modeling
- Assessment
    - Condition Assessment
    - Risk Assessment
    - Reliability, Availability, Maintainability and Safety (RAMS)
- Overall Asset Management

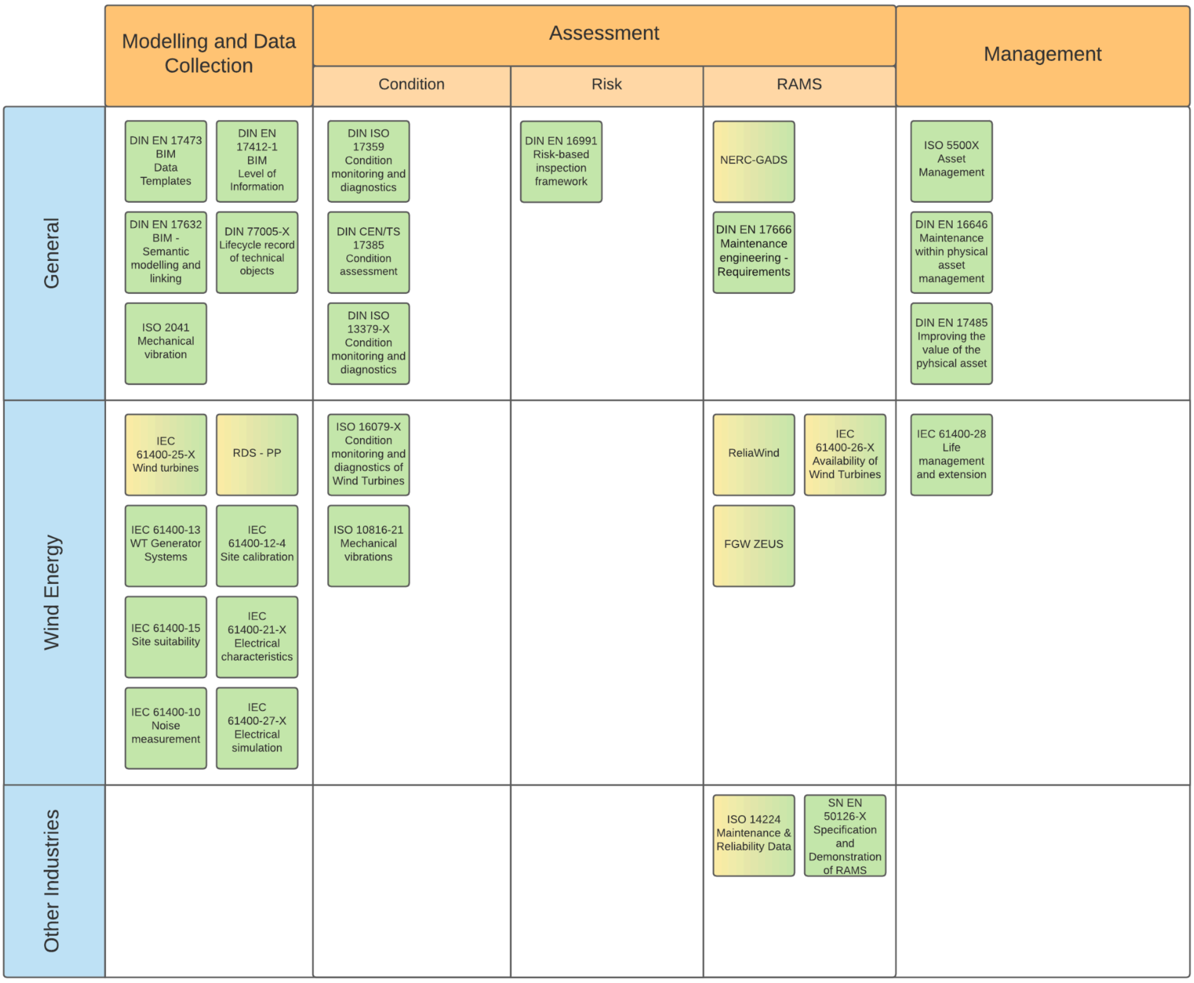
Within these value-chain stages, standards were further categorized according to their industry sector origin as follows and presented along the vertical axes.

Industry Sector Categories:
- General - non sector-specific, applicable to a broad range of industry sectors
- Wind Specific - wind industry focussed
- Other Industry Specific - specific to particular industry sectors

The investigation was conducted using a widely available internet search engine along with search terms that might be employed by a typical user e.g. “wind energy risk analysis standards”. Although internal company guidelines may be found, only standards and guidelines published by widely accepted industry bodies were considered, like ISO, IEC, and similar national standards organizations.

Discussion

The outcome from this exercise is summarized in **Figure 1**, below.



	Modelling and Data Collection	Assessment			Management
		Condition	Risk	RAMS	
General	DIN EN 17473 BIM Data Templates DIN EN 17412-1 BIM Level of Information DIN EN 17632 BIM - Semantic modelling and linking DIN 77005-X Lifecycle record of technical objects ISO 2041 Mechanical vibration	DIN ISO 17359 Condition monitoring and diagnostics DIN CEN/TS 17385 Condition assessment DIN ISO 13379-X Condition monitoring and diagnostics	DIN EN 16991 Risk-based inspection framework	NERC-GADS DIN EN 17666 Maintenance engineering - Requirements	ISO 5500X Asset Management DIN EN 16646 Maintenance within physical asset management DIN EN 17485 Improving the value of the pyhsical asset
Wind Energy	IEC 61400-25-X Wind turbines RDS - PP IEC 61400-13 WT Generator Systems IEC 61400-12-4 Site calibration IEC 61400-15 Site suitability IEC 61400-21-X Electrical characteristics IEC 61400-10 Noise measurement IEC 61400-27-X Electrical simulation	ISO 16079-X Condition monitoring and diagnostics of Wind Turbines ISO 10816-21 Mechanical vibrations		ReliaWind IEC 61400-26-X Availability of Wind Turbines FGW ZEUS	IEC 61400-28 Life management and extension
Other Industries				ISO 14224 Maintenance & Reliability Data SN EN 50126-X Specification and Demonstration of RAMS	

Figure 1: Result of standards search and categorization exercise.

Examining the Wind Energy row in the above diagram suggests that, with the IEC 61400 series, the sector is well catered for in relation to detailed technical and engineering standards and, to a lesser extent by a number of ISO standards.

In contrast, the upcoming IEC 61400-28 standard on “through life management and life extension of wind power assets” will reflect a broader asset management perspective and emphasize the importance of data analysis and on-going record-keeping in the context of life extension decisions.

The gap at the center of the Wind Energy row suggests that the wind energy industry may lack standardization around intermediate level topics such as risk-based inspection and maintenance assessment procedures. However, the standard DIN EN 16991 shown in the top row provides such general procedures for risk based inspection and maintenance for various industries, including the energy generating industry and possibly also the wind sector. DIN EN 16991 provides no industry specific proposals, but addresses risk-based maintenance in general. So, wind asset operators have to find out by themselves, whether to apply the standard or not.

More broadly, considering the top row of the diagram, there are many general standards which appear to be relevant to the wind sector across each of the main categories. These come from both international and national standardization bodies and may be readily applicable to the sector or may need to be adapted to address specific wind industry use cases.

Finally, the lower row indicates that other individual industry sectors may have already developed standards to address specific areas which might also be applicable to the wind sector.

While this manual exercise proved to be both cumbersome and complicated to navigate, it did serve to highlight a number of issues. Firstly, anyone attempting to ensure they utilize the most up-to-date and relevant standards will encounter obstacles (described in Table 1) similar to those experienced on this task. Secondly, even with a high-level picture of the standards landscape as shown, certain trends and opportunities can be identified, including reusability, adaptation of other sector's standards such as DIN EN 16991, etc. Lastly, there is an opportunity to develop tools to help navigate the standards landscape more efficiently.

A more detailed itemisation of the issues is provided in the Summary section and a proof-of-concept methodology for a more comprehensive, knowledge graph-based, approach to mapping the standards landscape is discussed later in the document.

Summary

The team collated the outcomes and experiences of the standards mapping exercise and reviewed with research and industry participants in IEA Wind Task 43. The consensus was that appropriate industry standards play a vital role in enabling digitalisation but a number of issues and observations can be highlighted. These are grouped under the FAIR [Wilkinson 2016] categories in **Table 1**.

Table 1: Issues and Observations identified by the Standards Landscape Mapping Exercise

FAIR Category	Issues and Observations
Findable	● Practitioners seeking to develop and implement a digitalisation solution can find it difficult to identify standards relevant to their specific implementation or use case. ● Relevant and appropriate standards may exist nationally or internationally but may not be generally applied in the industry. ● Standards do not fit easily into categories and the range of topics or use cases of some are too broad to align with the definitions used. ● The standards landscape cannot be readily described or visualized in a simple, two-dimensional space.
Accessible	● Actual standards documents tend to be hosted on separate proprietary commercial platforms which makes navigation and identification laborious. ● Also, the contents of many standards are restricted and only keywords are publicly presented.
Interoperable	● Standards have dependencies on other standards which may or may not be explicitly cross-referenced. ● Overlapping or possibly competing standards can be confusing and complicate the solution design effort. ● Where gaps may exist in wind industry standards, relevant and applicable standards may be available and transferable from other industry sectors.
Reusable	● New standards may be developed which are not strictly necessary as the areas may be covered in existing related standards. ● A significant amount of standards and guidelines specific to other industries, certain countries or regions, could be adopted by the wind industry. ● The wind industry should consider adopting the broad range of generic ISO standards (Management Systems, Product, Service and Health & Safety) as a complementary set of standards.

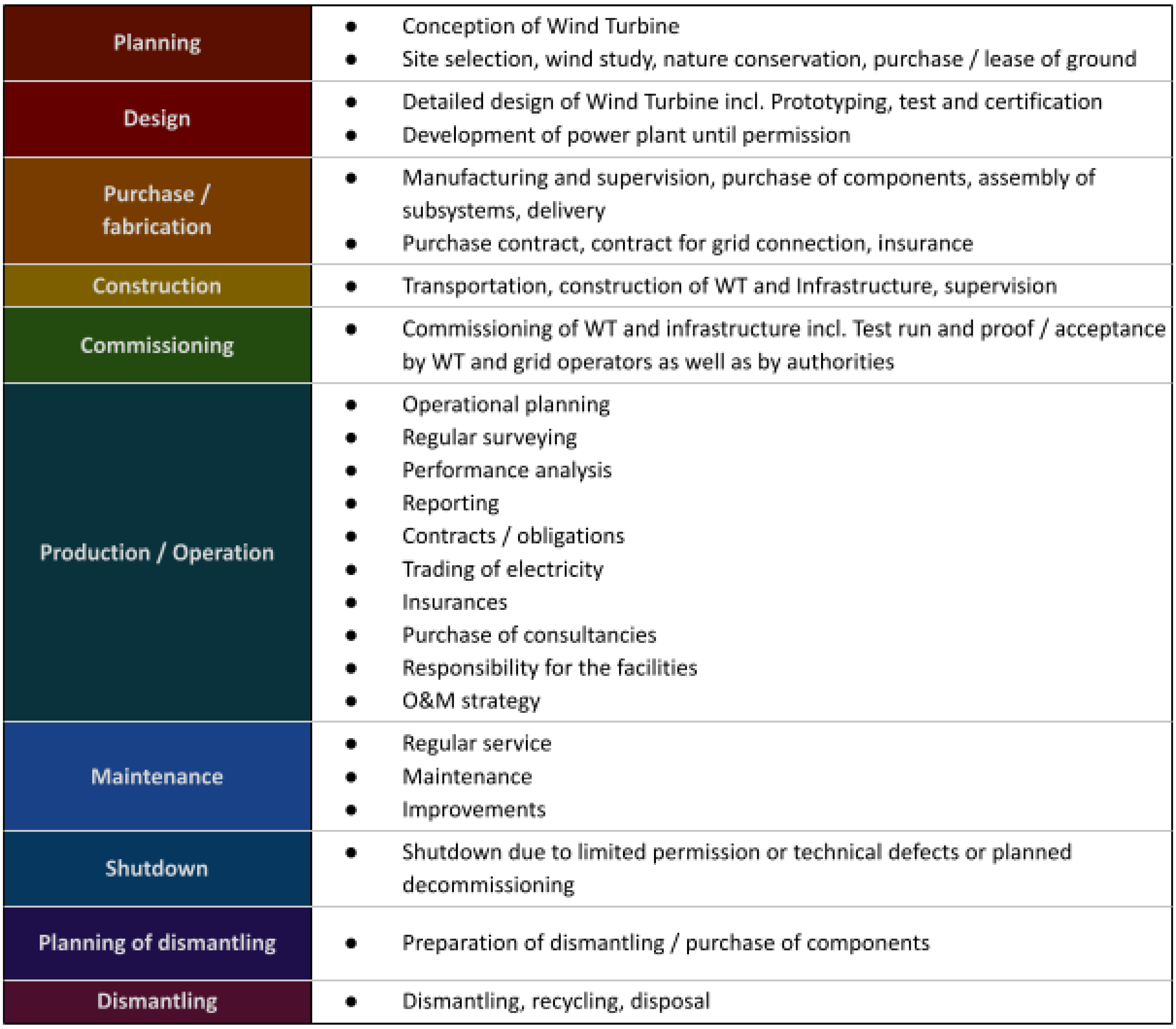
Framework for More Detailed Use Case Evaluation

The initial approach taken by the team attempted to identify standards gaps based on the high-level classifications in the matrix above. This provided a very coarse level of detail and an alternative user-centric approach was investigated and, therefore, a use cases-based classification was developed as described below. This may provide a basis for the future development of a more formal taxonomy.

In order to make use of the existing data, the data has to be properly collected, stored and documented. The FAIR principles for data management [Wilkinson 2016] propose to add a set of metadata to the actual dataset to describe it comprehensively. Since an asset steadily generates data from the start of its life cycle until it is discarded, the lifecycle stage of the power plant will be one important part of the set of metadata. Furthermore, the data goes through a data value chain from the generation until the start of the analysis. Typically, data go through a series of steps - each adding some value to the originally generated data - before it is mature enough to serve valuable analysis. Therefore, each step in the value chain requires specific metadata.
We suggest the wind energy sector consider these two aspects in the set of metadata describing actual datasets.

To this end, an evaluation template incorporating different product life cycle stages and data value chain stages is derived. To detail the dimension lifecycle stages, the group took a preliminary work result from FGW assigning tasks to lifecycle phases according to a meanwhile withdrawn national German standard (DIN SPEC 91303 *Components and structure of a plant documentation system for renewable energy plants*). **Table 2** depicts lifecycle stages and relevant tasks out of the internal working paper [FGW 2020].

Table 2: Lifecycle stages and tasks; Source: FGW internal work [FGW 2020]

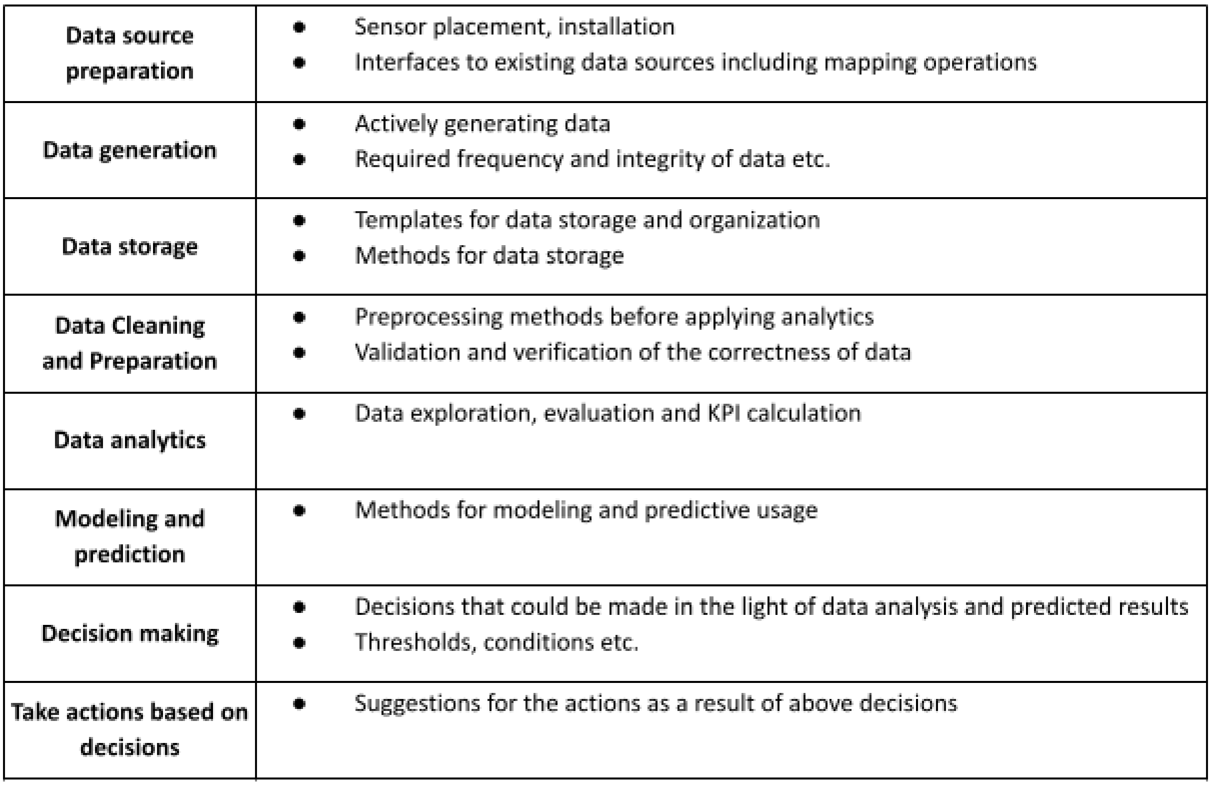


Planning	• Conception of Wind Turbine • Site selection, wind study, nature conservation, purchase / lease of ground
Design	• Detailed design of Wind Turbine incl. Prototyping, test and certification • Development of power plant until permission
Purchase / fabrication	• Manufacturing and supervision, purchase of components, assembly of subsystems, delivery • Purchase contract, contract for grid connection, insurance
Construction	• Transportation, construction of WT and Infrastructure, supervision
Commissioning	• Commissioning of WT and infrastructure incl. Test run and proof / acceptance by WT and grid operators as well as by authorities
Production / Operation	• Operational planning • Regular surveying • Performance analysis • Reporting • Contracts / obligations • Trading of electricity • Insurances • Purchase of consultancies • Responsibility for the facilities • O&M strategy
Maintenance	• Regular service • Maintenance • Improvements
Shutdown	• Shutdown due to limited permission or technical defects or planned decommissioning
Planning of dismantling	• Preparation of dismantling / purchase of components
Dismantling	• Dismantling, recycling, disposal

Product Life Cycle Stages

In collaboration with other teams within IEA Wind Task 43, the group identified different stages in the data value chain and corresponding tasks within each of the stages. **Table 3** depicts the suggested outcome.

Table 3 Data Value Chain stages and tasks, derived from Appendix B in [Barber 2023]

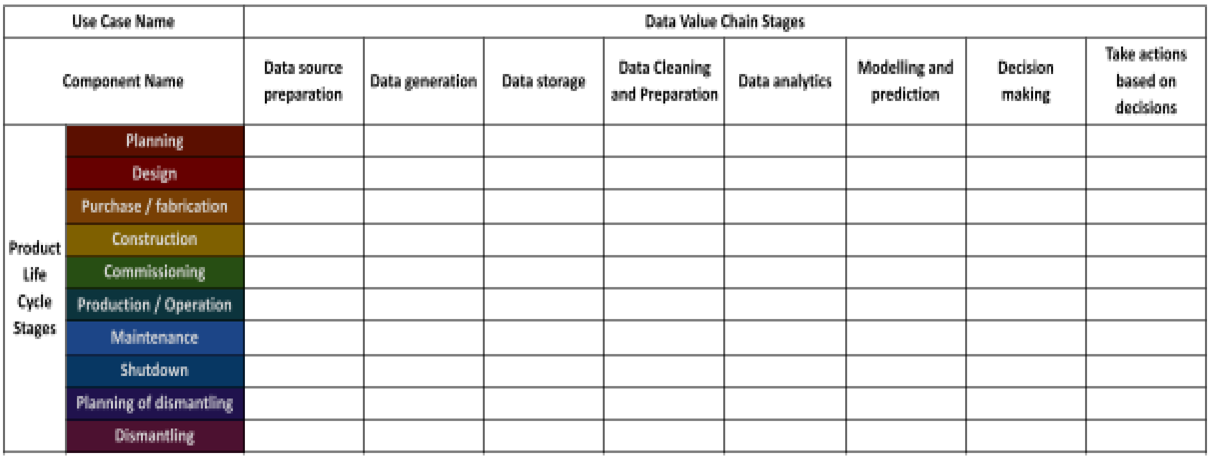


Data source preparation	• Sensor placement, installation • Interfaces to existing data sources including mapping operations
Data generation	• Actively generating data • Required frequency and integrity of data etc.
Data storage	• Templates for data storage and organization • Methods for data storage
Data Cleaning and Preparation	• Preprocessing methods before applying analytics • Validation and verification of the correctness of data
Data analytics	• Data exploration, evaluation and KPI calculation
Modeling and prediction	• Methods for modeling and predictive usage
Decision making	• Decisions that could be made in the light of data analysis and predicted results • Thresholds, conditions etc.
Take actions based on decisions	• Suggestions for the actions as a result of above decisions

Data Value Chain Stages

The combination of both the lifecycle stages and the data value chain stages lead to the matrix, shown in **Table 4**, which provides a possibility to sort challenges in the digitalization process into a structure.

Table 4: Matrix of lifecycle stages and data value chain stages building a taxonomy for outlining challenges in the digitalization in the wind energy sector.



Use Case Name		Data Value Chain Stages							
Component Name		Data source preparation	Data generation	Data storage	Data Cleaning and Preparation	Data analytics	Modelling and prediction	Decision making	Take actions based on decisions
Product Life Cycle Stages	Planning								
	Design								
	Purchase / fabrication								
	Construction								
	Commissioning								
	Production / Operation								
	Maintenance								
	Shutdown								
	Planning of dismantling								
	Dismantling								

Use Case Evaluation Template

The asset/lifecycle matrix described above is a working definition to help analyze various aspects of digitalisation. Its usefulness could be enhanced, and contribute further to asset value, if developed, standardized and shared in the industry. This will form one of the recommendations from the IEA Wind Task 43 team.

Detailed Investigation of Specific Use Cases

To further assess how digitalization efforts are helped or hindered by standards / taxonomies, specific use cases were examined in more detail and the potential to improve them with additional standards was identified.

The first use case, Risk-Based Maintenance, relates to the challenge of identifying O&M cost reduction opportunities and the second, Digital Processing of Maintenance Information, focusses on extracting insights for disparate sources of maintenance data.

The main findings are that the Risk-Based Maintenance use case is hampered by the absence of standards while standards are available to support the Processing of Maintenance Information but these may not necessarily be sufficiently adopted.

Use Case - Enabling Risk-Based Maintenance for Blades Through Digitalisation

Asset owners typically schedule regular blade inspections and, based on these, must decide whether corrective action should be taken to address either structural or performance implications. At present, there are few standards or guidelines for assessing inspections results or for systematically evaluating them in order to decide a course of action. This use case explored digitalisation-based approaches to address this challenge.

The problem

Blades are complex structures, with complex dynamics and designs varying across blade types which makes blade inspection and repair decisions difficult. Additionally, the implications of blade damage are difficult to assess based on a surface photo. This means that, operationally, blades must be repaired before damage becomes fatal while not incurring unnecessary costs by repairing earlier than required. Furthermore, repair decisions are largely driven by individual judgment, which can vary significantly, thus it often remains unclear how to balance costs and risks.

Current situation

Damage and defects are the leading causes of blades not reaching their intended design strength objects (e.g., lifetime and/or resistance to extreme loads) [Drewry 2007, Myrent 2022]. Blade maintenance programs seek to control (i.e., monitor or remediate) damage and defects such that the blade can achieve its design goals. Additionally, a robust blade maintenance strategy efficiently identifies and remediates blade defects and/or damages such that blade-related operational risks are mitigated to levels consistent with the stakeholders' risk tolerance. Current practice in blade maintenance ranges widely across the industry. Two key elements of a comprehensive blade maintenance strategy are:

1. Understanding blade condition, through

    a. structured approach to scheduling and executing external and internal inspection and
    b. consistent damage/defect identification and categorization.
2. Management of damage and defects, including
    a. monitoring and prioritization of repairs driven by data, knowledge, and experience and
    b. effective and efficient remediation.

While industry is converging on a 5-level categorization scheme, actual usage of that scheme at the most severe levels is highly variable. In most cases, damage inspection decisions are made based purely on visual inspection data, and by an individual with their own internal biases and experiences. This lack of consistency leads to subjective diagnosis, categorization and maintenance responses.

A Solution

One approach to reducing subjectivity is to utilize structured decision modeling to determine the lowest cost option between repairing now or reevaluating at the next inspection.

Bayesian decision modeling, in conjunction with a damage propagation model, provides a methodology to assess the probability-weighted costs for each decision branch alternative, allowing the lowest cost/risk option to be determined within given constraints.

Maintenance decisions typically seek to minimize costs, including costs of downtime, costs of repairs, and potential loss of production due to delaying repairs. Risk (expressed as a cost) associated with failure is more challenging to capture and is also a key part of determining appropriate maintenance actions to take.

The critical factor in blade maintenance decisions is understanding the rate that damage will propagate. Damage propagation is a complex phenomenon in composite materials that are subject to variable loads and a continuously changing environment. As the industry continues to work collaboratively to consolidate experience with damage propagation, we will be able to

model it with increasing accuracy. Until then, damage propagation rates are the main source of uncertainty in decision making.

Decision theory offers a rational approach to maintenance actions. Decision theory is a branch of mathematics which offers various optimized or non-optimized approaches to decision making. A decision tree approach most closely models the decision-making process currently utilized in the wind industry, where decisions are made by individuals using their personal experience and judgment to decide on an action. For example, a human decision maker would assess the severity and criticality of a blade damage or defect, take into consideration what he or she knows about the blade design, environmental conditions, operating conditions, historical damage, at that site, prior repairs, etc., and decide whether to repair or delay the repair based on his or her evaluation of the total cost and risks.

In contrast, a decision tree model would take this same decision approach and standardize it in a mathematical model. This allows application of consistent judgment and knowledge across all blade maintenance decisions, providing many benefits:

- **Standardization**: the same damage or defect would be addressed the same way no matter who is making the decision.
- **Traceability**: all involved can understand what is driving decisions, and if it is desired to improve processes, it is clear how and where investments can be made.
- **Consolidation of knowledge:** disparate sources of knowledge around a company can be consolidated into one model that then can be applied across all wind projects in a fleet.

Figure 2 depicts a possible decision tree for a risk-based decision model for blade repairs.

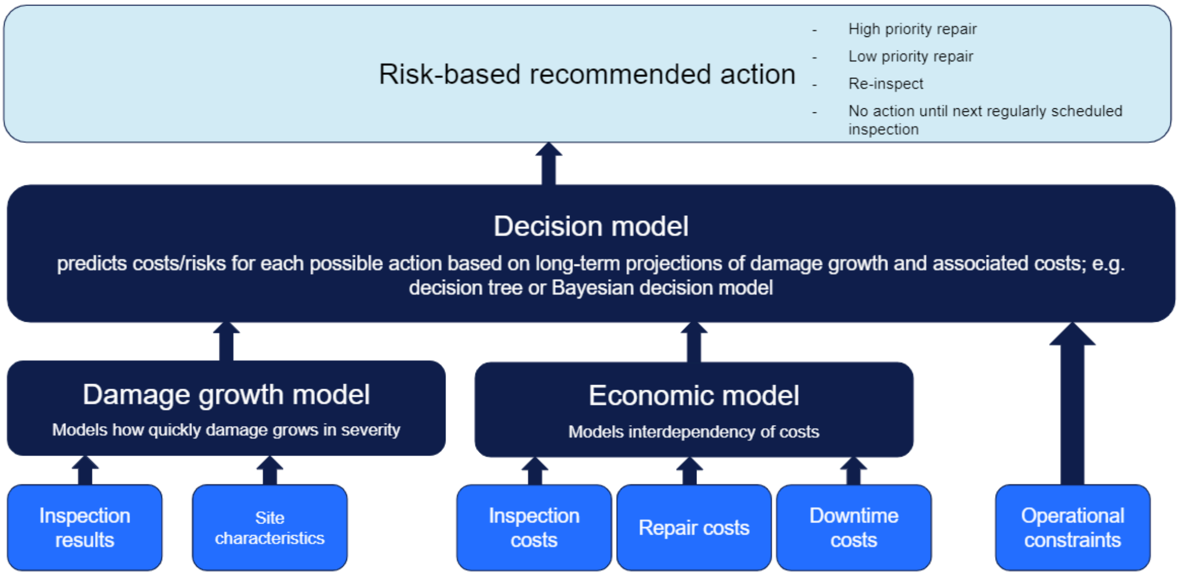
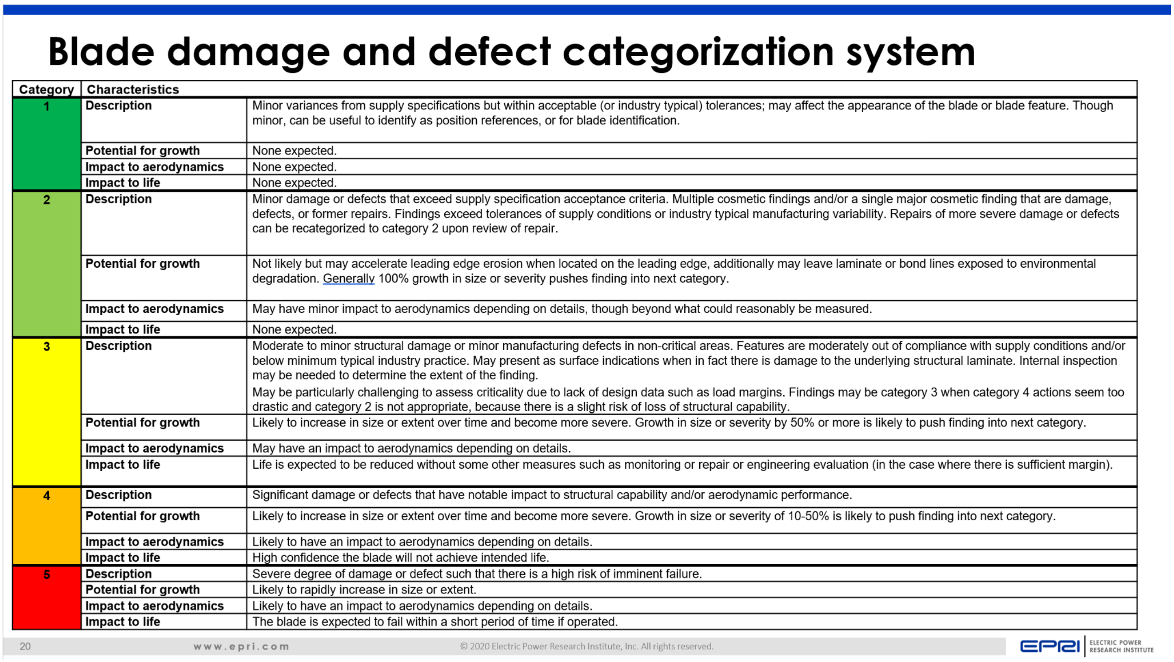


Figure 2: Example blade repair risk-based decision model [Byrne 2021]

Additionally, blade damage is typically categorized by severity on a scale from 1 to 5, where 1 is the least severe and 5 is the most severe. **Figures 3** and **4** below show an example of a blade damage and defect categorization scheme, developed and derived by EPRI via industry feedback [Myrent 2022].



Blade damage and defect categorization system

Category	Characteristics	
1	**Description**	Minor variances from supply specifications but within acceptable (or industry typical) tolerances; may affect the appearance of the blade or blade feature. Though minor, can be useful to identify as position references, or for blade identification.
	Potential for growth	None expected.
	Impact to aerodynamics	None expected.
	Impact to life	None expected.
2	**Description**	Minor damage or defects that exceed supply specification acceptance criteria. Multiple cosmetic findings and/or a single major cosmetic finding that are damage, defects, or former repairs. Findings exceed tolerances of supply conditions or industry typical manufacturing variability. Repairs of more severe damage or defects can be recategorized to category 2 upon review of repair.
	Potential for growth	Not likely but may accelerate leading edge erosion when located on the leading edge, additionally may leave laminate or bond lines exposed to environmental degradation. Generally 100% growth in size or severity pushes finding into next category.
	Impact to aerodynamics	May have minor impact to aerodynamics depending on details, though beyond what could reasonably be measured.
	Impact to life	None expected.
3	**Description**	Moderate to minor structural damage or minor manufacturing defects in non-critical areas. Features are moderately out of compliance with supply conditions and/or below minimum typical industry practice. May present as surface indications when in fact there is damage to the underlying structural laminate. Internal inspection may be needed to determine the extent of the finding. May be particularly challenging to assess criticality due to lack of design data such as load margins. Findings may be category 3 when category 4 actions seem too drastic and category 2 is not appropriate, because there is a slight risk of loss of structural capability.
	Potential for growth	Likely to increase in size or extent over time and become more severe. Growth in size or severity by 50% or more is likely to push finding into next category.
	Impact to aerodynamics	May have an impact to aerodynamics depending on details.
	Impact to life	Life is expected to be reduced without some other measures such as monitoring or repair or engineering evaluation (in the case where there is sufficient margin).
4	**Description**	Significant damage or defects that have notable impact to structural capability and/or aerodynamic performance.
	Potential for growth	Likely to increase in size or extent over time and become more severe. Growth in size or severity of 10-50% is likely to push finding into next category.
	Impact to aerodynamics	Likely to have an impact to aerodynamics depending on details.
	Impact to life	High confidence the blade will not achieve intended life.
5	**Description**	Severe degree of damage or defect such that there is a high risk of imminent failure.
	Potential for growth	Likely to rapidly increase in size or extent.
	Impact to aerodynamics	Likely to have an impact to aerodynamics depending on details.
	Impact to life	The blade is expected to fail within a short period of time if operated.

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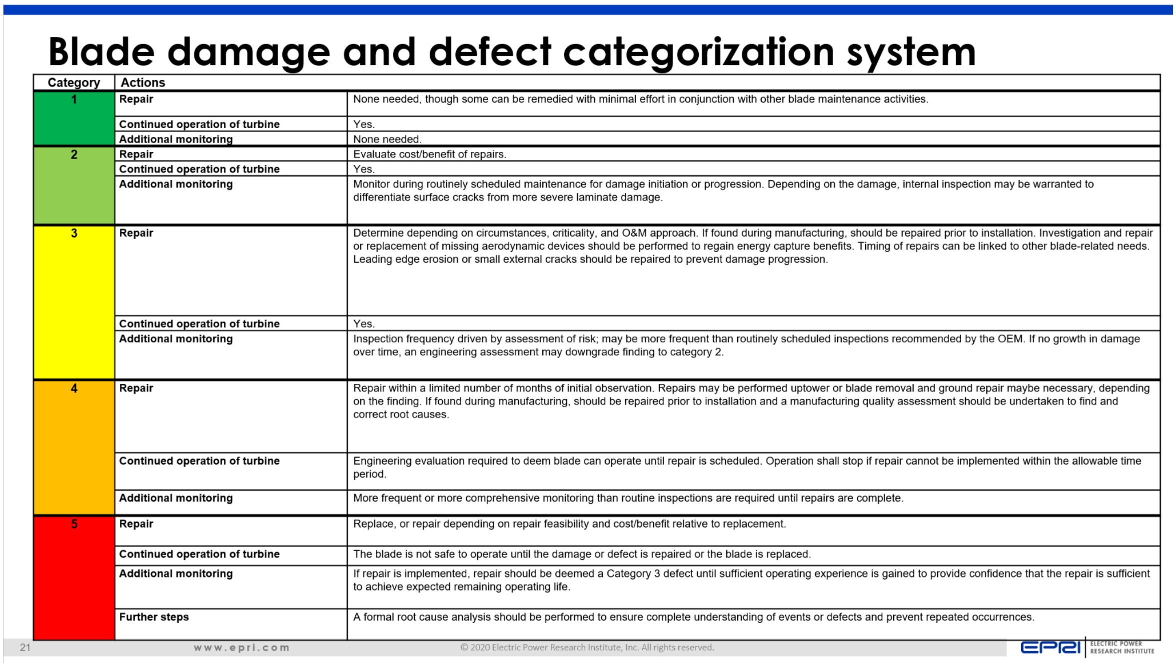
Figure 3: Example descriptions of blade damage and defect severity



Blade damage and defect categorization system

Category	Actions	
1 🟩	**Repair**	None needed, though some can be remedied with minimal effort in conjunction with other blade maintenance activities.
	Continued operation of turbine	Yes.
	Additional monitoring	None needed.
2 🟩	**Repair**	Evaluate cost/benefit of repairs.
	Continued operation of turbine	Yes.
	Additional monitoring	Monitor during routinely scheduled maintenance for damage initiation or progression. Depending on the damage, internal inspection may be warranted to differentiate surface cracks from more severe laminate damage.
3 🟨	**Repair**	Determine depending on circumstances, criticality, and O&M approach. If found during manufacturing, should be repaired prior to installation. Investigation and repair or replacement of missing aerodynamic devices should be performed to regain energy capture benefits. Timing of repairs can be linked to other blade-related needs. Leading edge erosion or small external cracks should be repaired to prevent damage progression.
	Continued operation of turbine	Yes.
	Additional monitoring	Inspection frequency driven by assessment of risk; may be more frequent than routinely scheduled inspections recommended by the OEM. If no growth in damage over time, an engineering assessment may downgrade finding to category 2.
4 🟧	**Repair**	Repair within a limited number of months of initial observation. Repairs may be performed uptower or blade removal and ground repair maybe necessary, depending on the finding. If found during manufacturing, should be repaired prior to installation and a manufacturing quality assessment should be undertaken to find and correct root causes.
	Continued operation of turbine	Engineering evaluation required to deem blade can operate until repair is scheduled. Operation shall stop if repair cannot be implemented within the allowable time period.
	Additional monitoring	More frequent or more comprehensive monitoring than routine inspections are required until repairs are complete.
5 🟥	**Repair**	Replace, or repair depending on repair feasibility and cost/benefit relative to replacement.
	Continued operation of turbine	The blade is not safe to operate until the damage or defect is repaired or the blade is replaced.
	Additional monitoring	If repair is implemented, repair should be deemed a Category 3 defect until sufficient operating experience is gained to provide confidence that the repair is sufficient to achieve expected remaining operating life.
	Further steps	A formal root cause analysis should be performed to ensure complete understanding of events or defects and prevent repeated occurrences.

Figure 4: Example actions for blade damage and defect severity categorization

Gap Analysis

Table 5 describes the blade data value chain throughout the component's lifetime. Wind turbine blades are critical assets and several data sources are streamed and collected, on and off the turbine, throughout the blade's lifetime. Therefore, a plethora of data is needed in order to comprehensively characterize blade health, reliability and performance. The parameters described in the table can be utilized to maximize operational lifetime and performance of blades.

Typically, a wind turbine operator does not possess all of the data sources described in the table and this can result in lost opportunities. For example, a deeper understanding of inherent blade flaws discovered in the design and manufacturing phases can guide blade monitoring and inspection strategies in the field [Clifton 2023].

Another example is the need for more standardization on blade decommissioning [Beauson 2022]. In order to maximize the opportunity for reuse, new guidelines and standards to design wind turbine blades including end-of-life considerations should also be explored.

Lastly, as offshore wind continues to scale up, then standards need to keep pace to address, for example, more thorough evaluation of design aspects such as buckling and fatigue. [Roach 2020].

There are several entities involved in the standardization and best practices related to wind turbine rotor blades. Most commercial blade manufacturers choose to use DNV (formerly DNV-GL; GL) certification to provide their customers with additional evidence that the blades are designed and manufactured to stringent requirements. Another entity, the International Electrotechnical Commission (IEC), also provides detailed literature for the design of rotor blades. The IEC continually updates and reviews document IEC 61400, which specifies essential design requirements to ensure the engineering integrity of wind turbines. Its purpose is to provide an appropriate level of protection against damage from all hazards during the turbine lifetime. Specific to blades is IEC TC-88-5. IEC is not a certification body but offers standards that reflect best practices and are not obligatory.

The level of testing required to achieve appropriate operational certification from DNV or other certification bodies usually includes static and dynamic testing of a production rotor blade. The objective of this testing is to certify the blade is able to achieve and surpass the design requirements that will be experienced during operation.

Table 5: Blade lifecycle and data value chain

	Data Value Chain				
Blade Lifecycle Phase	**Data source preparation**	**Data generation**	**Data storing**	**Data Cleaning and Data Set Preparation**	**Data analytics**
Planning	Site development consulting report, site development model or simulation data	Unstructured Event Data in textual form, model or simulation outputs	Digital/ Paper	High Effort	Detailed failure models, in combination with sensor data, for root cause analysis, reliability analysis, performance optimization
Design					
Purchase / fabrication	Appropriately certified Blade manufacturer specification sheet.	Unstructured Event Data in textual form	Digital/ Paper	High Effort	Detailed failure models, in combination with sensor data, for root cause analysis, reliability analysis, performance optimization
Construction	Component lists, installation work instructions	Unstructured Event Data in textual form	Digital/ Paper	High Effort	Detailed failure models, in combination with sensor data, for root cause analysis, reliability analysis, performance optimization
Commissioning	Turbine commissioning reports	Unstructured Event Data in textual form	Digital/ Paper	High Effort	Detailed failure models, in combination with sensor data, for root cause analysis, reliability analysis, performance optimization
Production / Operation					
SCADA	Sensor Measures (10 min avg,min, max, std)	Structured, Time Series	Digital	Medium Science	Normal Behaviour Models for predictive maintenance, Performance Measures, Underperformance
SCADA	Status Codes (or Alarm logs, Alarm Codes, Status Logs)	Structured Event Data triggered by the WT	Digital	Low Effort	Frequent pattern mining for predictive maintenance purposes, Root cause analysis
SCADA	Trace Files (High Frequency Sensor measures before WT outages < 10 min Duration)	Structured, Time Series; Examples include vibration, acoustic, acoustic emissions, strain	Digital	Medium Effort	Root cause analysis
SCADA	Sensor Measures (1 Hz Measures)	Structured, Time Series	Digital	Low Effort	Normal Behaviour Models for predictive maintenance, Performance Measures
SCADA	Structural Health and Condition Monitoring - Usually <1 Hz Measures, part of SCADA	Structured, Time Series	Digital	Low Effort	Normal Behaviour Models for predictive maintenance, Performance Measures
SCADA	Operational Modes (Event Classification)	Partly Structured, Differs from Operator to operator, Event Data, either triggered by the WT or assigned by the WT operator	Digital	Low Effort	High Level Failure Models in combination with sensor data
Maintenance					
	Maintenance Work Orders (could be available in Operational/Asset Management Systems)	Unstructured Event Data in textual form	Digital	High Effort	Detailed Level Failure Models in combination with sensor data, Root cause analysis
	Up-tower inspection data including observations, high definition camera, radiographic, ultrasonic, thermographic	Unstructured Event Data in textual form, images of blade sections	Digital	High Effort	Detailed Level Failure Models in combination with sensor data, Root cause analysis, performance optimization
	Down-tower inspection data including telephoto lens, high definition camera, or drone	Unstructured Event Data in textual form, images of blade sections	Digital/Paper	High Effort	Detailed Level Failure Models in combination with sensor data, Root cause analysis, performance optimization
	Spare Parts Inventory	Structured/Unstructured spreadsheet	Digital/Paper	High Effort	Maintenance planning
	Permit to Work Orders (could be available in Operational/Asset Management Systems)	Unstructured Event Data in textual form	Digital	High Effort	Maintenance planning in-house and with third party blade specialists
	Warranty/Claims/Damage Reports	Unstructured Event Data in textual form	Digital/Paper	High Effort	Root cause analysis
	Operational Modes (Event Classification)	Unstructured Event Data in textual form	Digital	Low Effort	High Level Failure Models in combination with sensor data
Shutdown	Status Codes (or Alarm logs, Alarm Codes, Status Logs)	Structured Event Data triggered by the WT	Digital	Low Effort	Frequent pattern mining for predictive maintenance purposes, Root cause analysis
Planning of dismantling	Spare parts/ inventory planning, replacement/recycling/disposal strategy	Unstructured Event Data in textual form	Digital/Paper	High Effort	Due Diligence

Dismantling	Spare parts/ inventory planning, replacement/recycling/disposal report	Unstructured Event Data in textual form	Digital/Paper	High Effort	Due Diligence

Overall, there are several reference standards which have been utilized to derive industry-specific standards for wind turbine blades. Several of the reference standards lack applied methodologies in terms of the overall blade lifecycle and fusing together different blade data sources for analysis. Further standardization in this space will drive a more comprehensive blade health management strategy.

Use Case - Digital Processing of Maintenance Information

The following use case outlines the issues involved in processing various sources of maintenance data and recommends standards that should be used in the documentation of the maintenance activities. The proposed solution is briefly discussed and following actions are explained. It is outlined in [Lutz 2022] in more detail.

The Problem

Maintenance of wind turbines generates a lot of information which is shared among the involved stakeholders, such as service reports, maintenance work orders, inspection reports, and invoices. However, often the documentation is typically enterprise-specific, does not apply common structures and does not follow standards or technical guidelines. Additionally, documents are available in the form of PDFs, csv, xlsx or txt-files, so that users cannot directly process it digitally in enterprise resource planning systems or in other data sinks. Therefore, although these documents contain much relevant data, often this source of information remains untapped and the calculation of high quality key performance indicators is therefore hindered.

Recommended Standards

Recommended practices for wind farm data and reliability assessment are described in [Hahn 2017]. Those practices support the usage of RDS-PP® [vgbe 2016] and ZEUS [FGW 2013]. More recent activities also focus on the usage of RDS-PS [ISO 2022] or the revision of GSP [FGW 2014].

Currently, maintenance information is typically neither structured nor standardized. By using the standards above, maintenance information could be structured in a uniform, standardized manner. This enhances and eases cross-company communication and enables the assessment and calculation of reliability KPIs and further analysis.

Proposed Solution

To overcome this problem, we propose the digitalization workflow. The workflow can be seen in **Figure 5**. The steps of the workflow are optical character recognition, information extraction and text classification. By using the workflow, maintenance information can be automatically structured and standardized into recommended standards or guidelines. The steps and the process is more elaborately described in [Lutz 2022]

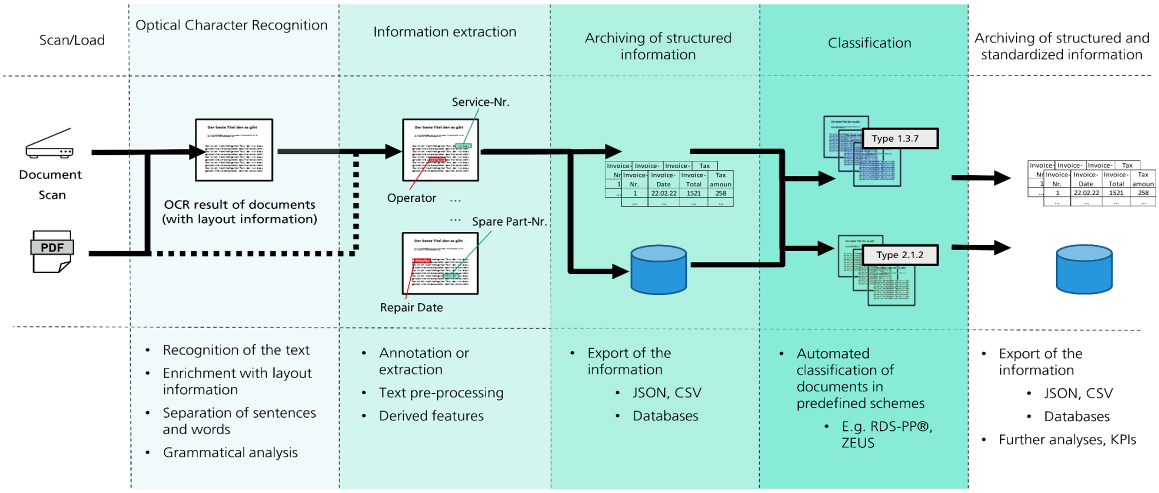


Figure 5: Digitalization Workflow for Maintenance Reports [Lutz 2022]

First, maintenance information that is available as scanned images is converted into machine readable text. Therefore documents that are only available as scanned images can be made available for machine processing of the information contained. Second, different information categories in different service reports need to be converted into a common structure. This is automated in the Information Extraction step. In this way, structured information is available where each row contains one report and related categories are grouped into columns. However, some information categories are still not standardized (for example,the text description of the maintenance measure described in the wind turbine service report). Third, by using text classification, this text and the associated metadata, could automatically be assigned with an appropriate schema according to a standard or a technical guideline. In the above example, the component that is referenced in the textual description of the maintenance activity can be classified according to RDS-PP [vgbe 2016] or RDS-PS [ISO 2022], while its status can be classified according to ZEUS [FGW 2013].

Thus instead of unstructured raw text, an activity is described in a uniform way. In other words, this taxonomy adds context and structure to otherwise unstructured data. Following the completion of the above described steps, structured standardized information is available, allowing for further analysis. For example, reliability KPIs can be calculated, allowing for better planning of future wind turbine maintenance activities. Additionally, the use of common language eases cross-company communication, which avoids misunderstandings and saves time. Ultimately, the levelized cost of energy could be decreased by implementing the workflow.

Conclusions

Both use cases outlined above reflect scenarios where additional value and decision-support capability could be extracted from data but the ability to do so is hampered by an inadequate standards ecosystem.

In the Blade Risk-Based Maintenance case, the overall situation is one where relevant standards are available but, with insufficient industry co-ordination, there are gaps and overlaps in their coverage of key areas.

The situation with the Maintenance Information use case is somewhat different in that a set of standards does exist which largely addresses the scenario described. However, those standards are, at present, not widely adopted.

Furthermore, the Maintenance Information use case, if fully realized, would be of significant value in supporting, among others, the Blade Risk-Based Maintenance objectives.

Different standards and guidelines exist for activities throughout the asset lifecycle but there are gaps and overlaps. For example, standards for blade certification conditions may not consider all relevant operational conditions and, conversely, there are no guidelines to allow actual usage patterns to be comprehensively monitored and fed back to the design/certification phase. Similarly, manufacturing data is not readily available to operators.

Furthermore, different monitoring methods, even for fundamental measurements like wind speed, are recommended across the lifecycle which can lead to inconsistent application of data. Or, for design functionality, like blade lightning protection systems, there may not be sufficient guidelines to enable structural or performance verification during operation.

There is the additional challenge of overcoming the low adoption rates of certain standards, possibly because the value of data is still not clear to owners/operators or because they have difficulty identifying and navigating relevant and sometimes inconsistent standards.

The overall conclusion is that, while there are standards and guidelines that facilitate digitalisation within the wind energy sector, there is further opportunity to bridge gaps in the standards and facilitate a more streamlined approach to enhancing digitalisation capability.

Some of the gaps may arise because it can be difficult to identify which standards are applicable to particular use cases. For example, uncertainty quantification in wind energy projects.

There is an opportunity for the wind industry to adapt or adopt existing standards and best practices and to invest in better solutions to consolidating and navigating the standards landscape.

Another observation from the gap analysis exercise was that standards should consider defined use cases in order to improve their FAIR characteristics (Findable, Accessible, Interoperable and Reusable). This and other measures to improve FAIR properties are discussed in the following section.

Towards a FAIR standards ecosystem

The acronym FAIR normally refers to the desirable characteristics of data in general but could also be applied to wind energy standards with interpretation as in **Table 6**:

Table 6: Suggested characteristics of standards meeting the demands of the FAIR principle

Category	Standards Characteristic
Findable	Readily identify standards relevant to the digitalisation or business opportunity at hand
Accessible	Ability to locate the full content of a standard
Interoperable	Standards are constructed in such a way that their functionality can be implemented directly in digital applications, for example coded functionality can be imported into a software application.
Reusable	The goal is to optimize the reuse of standards. Thus, definitions and recommendations should be well-described so that standards can be replicated and/or combined in different settings

This group developed a proof of concept for a tool based on a graph database which could help improve the FAIR characteristics of standards. By mapping the relationships between standard, keywords and life cycle stages this tool could be used to identify related standards. See **Figure 7**, where selected life cycle keywords are used to find related standards, some of which can be related to multiple keywords. This would also work in the opposite direction, meaning that with one standard it is possible to see its corresponding keywords, as in **Figure 6**.

The group intends to further develop the proof of concept into a valuable tool for the wind industry and is considering incorporating the functionality to allow end users to directly populate the database with standards and keywords. [POC 2024]

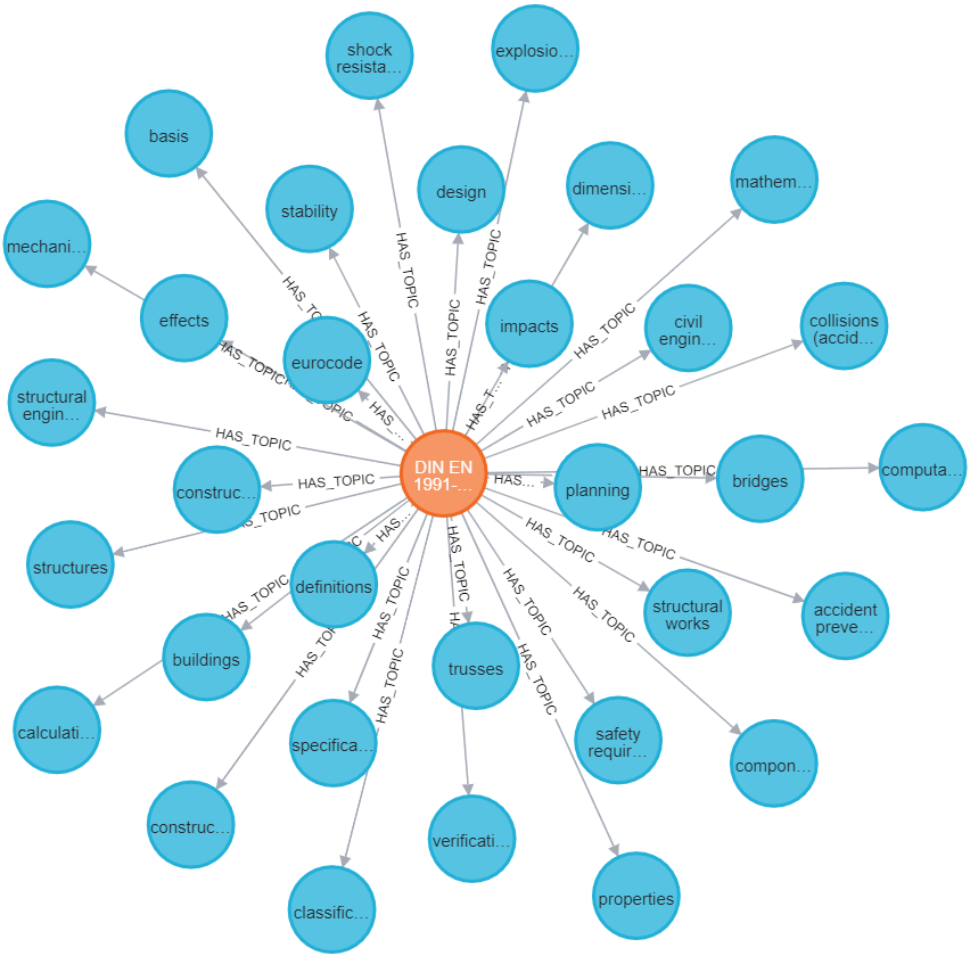


Figure 6: Graph of connections between name: DIN EN 1991-1-7 standard (orange circle) and its related keywords (blue circles).

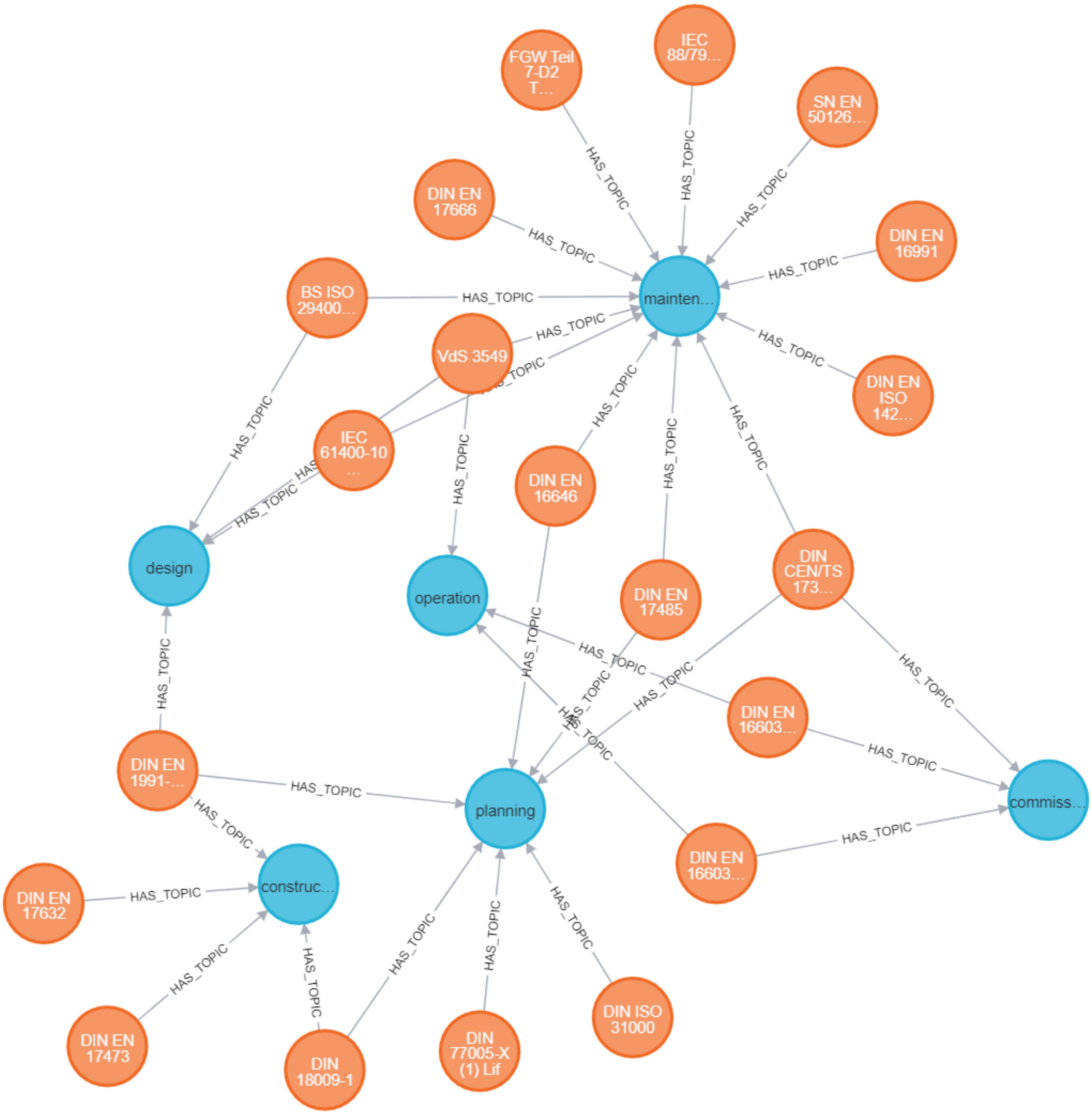


Figure 7: Graph of connections between a subset of available keywords belonging to asset lifecycle stages and their respective standards. The blue circles show different keywords and the orange circles show different standards.

The standards within the wind energy sector were developed by a diversity of industry bodies, each with different sets of stakeholders and contexts in mind. Different stakeholders will often have different perspectives on data assets. These different perspectives, and associated understandings, can obfuscate potential synergy when developing standards.

The availability of common semantics would enable productive discussion and compromise, but may require a great deal of conversations, invested resources, and testing before being embraced by the wind energy sector. When developing semantic standards, it is ideal to start conversations between different stakeholders early. We hope that the presented database model will foster many conversations between different stakeholders within the wind energy sector.

As the database evolves, it may be useful to organize it in a hierarchical way. IEA Wind Task 33 analyzed several existing taxonomies in the context of collecting good quality data for reliability analyses. That taskforce found that an hierarchical ontology of terms would be beneficial and would, for example, allow the grouping of terms which represent all components of a turbine relating to a particular aspect of functionality. Following defined rules based on functional blocks would allow adding recently introduced components to the respective group at the correct level of detail. Additionally, those rules may assign alphanumeric codes to systems, sub-systems, modules and parts, which would be machine readable and could be translated into any language.

A variety of taxonomies/ontologies exists, defining terms for components, failures, O&M measures, etc., such as:

- RDS-PS 81346-10 DS/ISO 81346-10:2022 [ISO 2022]
- IRPWIND NEAT taxonomy [Sempreviva 2017]
- WindIO ontology [IEAWT37 2023]
- NERC GADS [NERC 2023]
- ZEUS [FGW 2013]

Life cycle stages might be an important attribute captured as metadata describing the context of data generation and/or usage. A working group of FGW suggests assigning goals and tasks of stakeholders to life cycle stages in a meaningful manner [FGW 2020]. The result given in **Table 7** may be useful for defining metadata.

Table 7: Suggestion from FGW for dividing the life cycle of wind turbines into stages and substages and for assignment to stakeholders

Life cycle stage	Life cycle sub-stage	Stakeholders
Preparation [Divided into the two paths of i) developing the turbine and ii) site planning]	**Planning** i) Technical concept of turbine ii) Site selection	i) Designer ii) Developer, consultant, grid operator
	Design i) Detailed designing of turbine ii) Development of power plant until permission	i) Designer ii) Developer
	Purchase / fabrication i) Manufacturing, purchase of components, … ii) Land purchase, permission of building and grid connection, insurance …	i) Manufacturer, supplier ii) Owner
	Construction Transportation, erection/installation of	Manufacturer

	turbine and infrastructure, supervision	
	Commissioning Commissioning of plant, test run, acceptance by grid operator and authorities	Manufacturer, supplier, certification body grid connection, grid operator, service provider, consultant
Usage	**Operation** Operational planning, Performance analysis, Reporting, Trading of electricity, Insurances, O&M strategy	Operator, grid operator, planner of maintenance services
	Maintenance Regular service, Maintenance, Improvements	Operator, planner of maintenance service, service provider
	Shutdown Shutdown due to limited permission or technical defects or planned decommissioning	Operator, Grid operator, permitting authority
Decommissioning	**Planning of dismantling** Preparation of dismantling / purchase of components	Developer, owner, operator
	Dismantling Dismantling, recycling, disposal	Owner

The investigation described in this document was invaluable in highlighting the challenges in navigating standards and guidelines when setting out a digitalisation strategy. The proposals in this section provide possibilities on how to address these challenges and further facilitate the application of digitalisation solutions.

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