Towards Efficient Operation and Maintenance of Wind Farms: Leveraging AI for Minimizing Human Error

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ABSTRACT

To effectively compete with other renewable energy sources, there remains a critical need to further decrease the Levelized Cost of Energy of Wind Farms (WFs). A promising way to achieve this objective is by minimizing the downtime of wind turbines (WTs) through effective Inspection and Maintenance (I&M) activities. Conventionally, I&M plans have predominantly relied on CM/SCADA data obtained from the physical components of turbines, with data analytics and machine learning (ML) techniques being employed to predict their performance and maintenance needs. However, statistics indicate that nearly 40% of WT failures can be traced back to HFs. These include aspects such as skills, knowledge, communication, and even the broader organizational culture. This paper delves into the importance of integrating HFs in the I&M of WFs to optimize turbine performance, enhance safety, and reduce downtime.

Firstly, we briefly discussed various Human Reliability Analysis (HRA) methods with special emphasis on Performance Shape Factors (PSFs). We then identify key human factors (HFs) that are vital for performing O&M tasks. For this, we have prepared a questionnaire to get qualitative input from technicians and also done a thorough literature review. E.g., some of the HFs that stand out include the ergonomics of tools and workspace designs tailored to technicians' needs, the cognitive load placed on operators during system monitoring and diagnostics, continuous training to handle evolving challenges, effective communication channels, and safety protocols designed with human behavior in mind. We then propose a novel framework for developing a computer vision-based recommendation system that can guide the technicians to perform the maintenance effectively thus minimizing the HE.

1. INTRODUCTION

The wind industry, driven by a commitment to green energy generation, is at the forefront of research, technological innovation, efficiency gains, and cost reductions. With turbine sizes and capacity factors having tripled, there has been a monumental shift in the wind energy sector. Since 1990, generation costs have been reduced by 65% (KPMG, (2019)), underscoring the industry's dedication to developing sustainable and economical energy solutions for the future. For instance, breakthroughs in blade design and materials, backed by rigorous research, enable turbines to harness wind more proficiently, yielding higher energy outputs even in suboptimal wind conditions (Asim, T., Islam, S., Hemmati, A., & Khalid, M. (2022)). The adoption of various Prognostics and Health Management (PHM) technologies and predictive analytics has further improved the operation and maintenance (O&M) of (WFs), curtailing downtime and driving costs even lower (Haghshenas, A., Hasan, A., Osen, O., & Mikalsen, E. T. (2023)).

Rinaldi et al. (Rinaldi, G., Thies, P. R., & Johanning, L. (2021)) performed an exhaustive survey of the latest strategies governing the O&M planning and CM of OWFs. Their review delves into the benefits and limitations of current practices and looks ahead to emerging trends in robotics, AI, and data analytics. Key opportunities highlighted include the integration of diverse data sources to refine O&M strategies, precise inventory management, detailed uncertainty modeling, the urgent need for

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standardized open data frameworks, and the development of essential reference software. In a related study, McMorland et al. (McMorland, J., Flannigan, C., Carroll, J., Collu, M., McMillan, D., Leithead, W., & Coraddu, A. (2022)) highlighted the significance of various factors in O&M modeling for OWFs, including weather dynamics, failure, and degradation patterns, vessel logistics, cost estimation, and maintenance tactics. Besnard et al. (Besnard, F., Patriksson, M., Stromberg, A. B., Wojciechowski, A., & Bertling, L. (2009)) introduced the 'opportunistic maintenance' concept for OWFs, which entails the fusion of multiple planned corrective and preventive maintenance tasks, either within a similar timeframe or even during a single visit. By capitalizing on wind forecasts and synchronizing corrective maintenance with periods of low power generation or unexpected failures, this approach has proven to yield a 43% reduction in preventive maintenance expenses (Fast, S., Mabee, W., Baxter, J., Christidis, T., Driver, L., Hill, S., McMurtry, J., & Tomkow, M. (2016)) However, as currently practiced, the PHM approach uses only machine-related quantitative data available from CM/SCADA systems to predict and manage the performance and maintenance needs of WFs. The biggest drawback of the overreliance on machine-related (MR) data is its inability to capture the full spectrum of operating conditions under which WFs function. A frequently undervalued metric in this context is human-related data, which offers additional insights into the system environment (Kiassat, A.C., (2013)).

Human technicians/operators are an essential part of the daily O&M activities of the WFs. It is highly probable that Human Error (HE), in one form or another, might infiltrate the design, manufacturing, operation, and maintenance phases of WFs. Morag et al. (Morag, I. et al. (2018)), identified the most common HE during a maintenance activity described in Table 1.

The HE may go unnoticed due to various reasons and can result in catastrophic accidents leading to severe consequences for the environment, society, and business. Statistics indicate, HE as one of the major factors for accidents across various sectors as shown in Figure 1. For instance, the infamous disasters within the oil and gas sector namely, the Piper Alpha and the BP Deepwater Horizon blowout occurred due to human and operational flaws. Likewise, the accident investigations of multiple aircraft crashes (such as of a Boeing 707-321C in 1977; Boeing 747-200, in 1992; and Airbus 380-842 Qantas Flight 32 in 2010) also point towards technical failures, HFs, and regulatory shortcomings as failure causes (Mathavara, K., & Ramachandran, G. (2022)). These statistics serve as a reminder that, while the hardware aspect is undoubtedly important, the human dimension also has a significant influence on the overall health and performance of the system.

Table 1. Most common causes of Human Errors

(Morag, I. et al. (2018))

HE Type	**Description**
Communication	Misunderstandings among technicians and operators, often stemming from inadequate leadership and management.
Fatigue	Tiredness due to overwork or working in enclosed environments.
Tools and equipment	Improper use of tools and equipment can augment risks and compromise worker safety. Additionally, the lack of proper tools may increase HE as workers resort to using unsuitable machinery for specific tasks.
Skills and expertise	The risk of HE increases in non-routine tasks that demand specific knowledge when workers assigned are unfamiliar with the activities.
Bad procedures	HE often arises from poor information and the lack of standardized procedures.
Documentation	Poor documentation handling can increase HE due to its impact on task performance and understanding of required work.
Procedure’s usage	Lengthy procedures often lead workers to adopt informal methods and rely on personal experience to complete tasks.
Time pressures	Overtime and overwork often lead to more mistakes by workers, as they resort to shortcuts and simpler work methods.
Tool control and housekeeping	It concerns tracking the equipment used or removed from machinery.

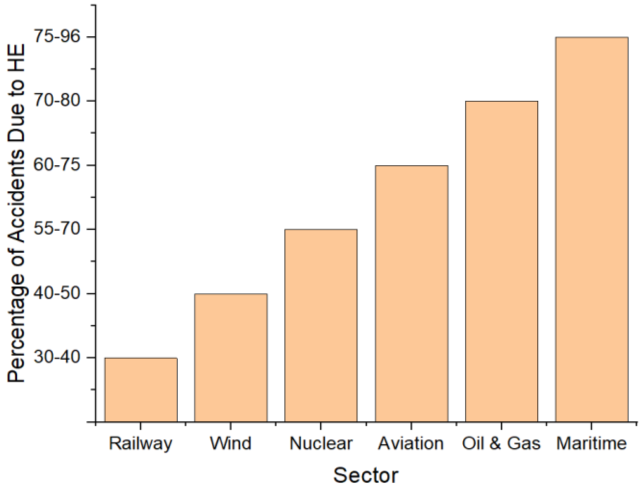

Figure 1. Accident percentage due to HE across various sectors

In this paper, the authors have highlighted the importance of integrating HFs within O&M of WFs. Firstly, we have briefly discussed various Human Reliability Analysis (HRA) methods with special emphasis on Performance Shape Factors (PSFs). We then discuss two scenarios of performance maintenance in the yaw deck and the nacelle of a typical WT. Thereafter we propose a framework for developing a computer vision-based recommendation system that can guide the technicians to perform the maintenance effectively thus minimizing the HE. We also propose the use of an eye-tracking device to measure the stress level of technicians.

2. HUMAN RELIABILITY ANALYSIS (HRA)

2.1. General

The origin of HRA is in probabilistic risk assessment (PRA), a discipline initially developed for understanding and quantifying the risks of serious accidents within the nuclear industry. HRA provides methods and tools for analyzing and assessing risks caused by operator's actions on a technical system, thus evaluating to operator's contribution to system reliability. The first fully developed HRA methods date back to the 1970s when systematic tools for analysis of the operator's contribution to risk were applied in the nuclear industry. There are now several HRA methods available for the nuclear sector, with some being adapted to other industries such as oil and gas, chemical, and aviation. Figure 2 illustrates the steps of a generic HRA process.

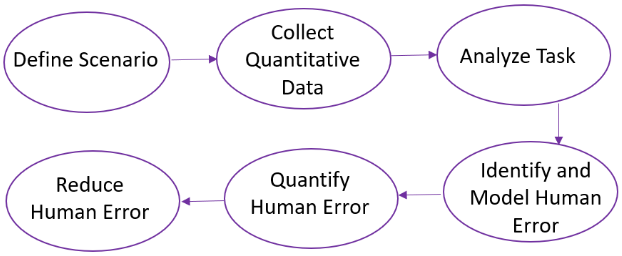

Figure 2. Generic HRA Process

2.2. HRA Methods

It is common to distinguish between first and second-generation HRA methods (Swain, A.D. (1990), Dougherty, E.M. (1990)). The list of first-generation methods is extensive and includes amongst others Technique for Human Error Rate Prediction (THERP) (Swain, A.D., Guttman, H.E. (1983)), the Human Cognitive Reliability method (HCR) (Hannaman, G.W., Spurgin, A.J., Lukic, Y.D. (1984)), the Human Error Assessment and Reduction Technique (HEART) (Williams, J.C. (1985)), Accident Sequence Evaluation Program (ASEP) (Swain, A.D. (1987), and Standardized Plant Analysis Risk – Human (SPAR-H) reliability analysis (Gertman, D., Blackan, H.S., Marble, J., Byers, J., Haney, L.N., Smith, C. (2005)). Hollnagel (Hollnagel, E. (1998)), and Kim (Kim, I.S. (2001)) provide the following list of notable characteristics of first-generation methods: 1) Assumption that human reliability is similarly describable as hardware reliability. 2) HRA being limited to only the human actions that are included in the PSA event trees. 3) Binary representation of human action as either success or failure to carry out a given task. 4) Dichotomy of errors of omission (failure to perform an action) and errors of commission (unintended or unplanned action). 5) Focus on phenomenological aspects of human actions. 6) Little concern about the cognitive aspects of human actions. 7) Emphasis on quantification of human errors. 8) Indirect treatment of context, as the way in which PSFs exert their effect on performance is not described.

Second-generation HRA methods were developed based on cognitive architectures to unveil the causes of errors from a behavioral perspective; thus, solving the main deficiency of the first generation. Two basic requirements proposed by Hollnagel (Hollnagel, E. (1998)) are that second-generation approach "uses enhanced PSA event trees and that it extends the traditional description or error modes beyond the binary categorization of success-failure and omission-commission" (p.151). He further stresses the need for a more realistic type of operator model, as the approach must be explicit about the way in which performance conditions affect performance. Most authors critiquing first-generation HRA methods agree on the necessity of incorporating a cognitive model into HRA "that would enable a better understanding of human error mechanisms that were well described by Reason (Reason, J. (1990))". A Technique for Human Event Analysis (ATHEANA) (Cooper, S.E., Ramey-Smith, A.M., Wreathall, J., Parry, G.W. (1996)) and Cognitive Reliability and Error Analysis Method (CREAM) (Hollnagel, E. (1998)) are examples of well-known and widely utilized second-generation techniques. CREAM uses the contextual control model (COCOM) and provides a determination of the reliability of a person's performance based on an error taxonomy that contains both error modes and error causes.

Although addressing the main issue of first-generation HRA methods, one of the highlighted weaknesses of second-generation methods is that they do not provide sufficient consideration of the mutual influences between PSFs (De Ambroggi, M. (2011)). According to Griffith and Mahadevan (Griffith, C.D., Mahadevan, S. (2011)) the main sources of deficiencies in HRA methods include: "1) lack of empirical data for model development and validation, 2) lack of inclusion of human cognition (i.e., need for better human behavior modeling, 3) large variability in implementation (i.e., HRA parameters are different depending on the method used), and 4) heavy reliance on expert judgment in selecting PSFs, and use of these PSFs to obtain the HEP in human reliability analysis" (p. 1444).

HRA experts have more recently begun to look at potential improvements to existing methods. As an example, the

HEART method has been used as a basis for domain-specific approaches such as Nuclear Action Reliability Assessment (NARA) (Kirwan, B., Gibson, H., Kennedy, R., Edmunds, J., Cooksley, G., Umbers, I. (2004)), Controller Action Reliability Assessment (CARA) (Kirwan, B., Gibson, H. (2008)), Railway Action Reliability Assessment (RARA) (Gibson, W.H., Mills, A.M., Smith, S., Kirwan, B.K. (2013)) and Shipboard Operations Human Reliability (SOHRA) (Akyuz, E., Celik, M., Cebi, S. (2016)). Another example is a more recent article by He et al. (He, Y., Kuai, N.-S., Deng, L.-M., He, X-Y. (2021)), which builds on CREAM by adding Human Inherent Factors (HIFs) such as anti-fatigue ability, concentration ability, reaction ability, and personality traits.

In 2006, NASA Office of Safety and Mission Assurance (OSMA) published a technical report evaluating 14 HRA methods against a list of 17 attributes to highlight methods that are considered suitable for use in risk and reliability studies of NASA space systems and missions. The evaluation resulted in the selection of four methods: THERP, CREAM, NARA, and SPAR-H. The list of attributes used to compare the methods included: Developmental Context, Screening, Task Decomposition, PSF List and Causal Model, Coverage, HEP Calculation Procedure, Error-Specific HEPs, Task Dependencies and Recovery, HEP Uncertainty Bounds, Level of Knowledge Required, Validation, Reproducibility, Sensitivity, Experience Base, Resource Requirements, Cost and Availability, as well as Suitability for NASA Applications (Chandler, F., Chang, Y., Mosleh, A., Marble, J., Boring, R., Gethman, D. (2006)). Consideration of several of these attributes is essential when evaluating existing HRA methods for use in the context of O&M of WFs.

2.3. Human Factors

Our definition of HFs is from IEA: "Human Factors is the scientific discipline concerned with the understanding of interactions among humans and other elements of a system, and the profession that applies theory, principles, data, and other methods to design to optimize human well-being and overall system performance". HFs can be used either in accident investigations, or they can be used to enhance the performance of the technicians.

The aims of using HF in general and in accident investigations are to:

(1) Improve safety (i.e., reducing the risk of injury and death);

(2) Improve performance in safety-critical situations (i.e., increase quality, productivity, and efficiency);

(3) Support satisfaction/usability (i.e., increasing acceptance, comfort, and well-being).

The details of how to use HFs for accident investigation are well documented in the literature, however, in this paper, we shall focus more on the identification of the HFs (in particular PSFs) that can be managed such that the I&M activities are performed efficiently within given time with minimal HE.

2.4. Performance Shape Factors (PSFs) for OWFs

PSFs or Performance Influencing Factors (PIFs) are defined by the Health Safety and Executive (HSE) as “characteristics of the job (e.g. the working environment); the individual (physical capability to do the work), and the organization (e.g. time pressure) that influence human performance” (HSE RR01 (2002))

Relevant PSFs for OWFs include environmental conditions (e.g., high winds, rough seas, weather variability), ergonomic challenges (working at heights, confined spaces, awkward postures), organizational aspects (training, work culture, resource availability), technical and mechanical complexity, accessibility and logistics due to remote locations, communication and coordination for emergency response, and the use of specialized tools and predictive maintenance technologies. On a more personal level, psychological stressors such as time pressure and distractions, as well as physiological factors like fatigue and hunger, can impact inspection and maintenance quality and error rates, especially in confined spaces like nacelles and hubs.

Acknowledging PSFs and their impact on operational outcomes is essential for ensuring the safety, efficiency, and reliability of OWF’s O&M. For instance, the performance of technicians can significantly drop on a wet and windy day compared to more favorable weather conditions, increasing the risk of human error and injuries. Similarly, an overloaded technician may overlook early signs of wear, potentially causing unforeseen equipment failures. Additionally, a company that prioritizes proactive maintenance is likely to emphasize regular training, which can lead to fewer operational errors.

The I&M activities and corresponding PSFs differ depending on the location within the WTs. For example, tasks on the yaw deck, such as brake maintenance and friction pad replacement, present unique challenges. These include transporting items using the nacelle crane or manually from inside the tower. Operations in this area entail inspecting the deck, handling moving parts, setting up the workspace, conducting maintenance, and cleaning up (G+ Global Offshore Wind Health & Safety Organization, (2021)). Challenges specific to the yaw deck include difficult access, particularly through ladder hatches in older turbines, constrained working space, and the physical strain of maneuvering heavy items. These conditions require technicians to employ specialized tools and assume strenuous postures, which can adversely affect their well-being (G+ Global Offshore Wind Health & Safety Organization, (2021)).

Most service and maintenance tasks in WTs, such as routine inspections and part replacements, are carried out in the confined spaces of the nacelle and blade hub. Although newer, larger wind turbines provide a bit more space and improved accessibility, the areas remain constrained, frequently cluttered, and occasionally slippery due to oil spills. These conditions make it difficult to move safely and operate tools efficiently (G+ Global Offshore Wind Health & Safety Organization, (2021)). In the hub, accessing components like blade root bolts forces technicians into uncomfortable positions, compounded by the presence of grease and cramped, angled spaces. This increases the likelihood of injuries, equipment mishandling, and errors. More details regarding PSFs for working on OWT can be found in (G+ Global Offshore Wind Health & Safety Organization, (2021)).

A questionnaire was designed to collect feedback from technicians, the results of which are presented in Figure 3 (in the Appendix). The questionnaire's link is provided in (Questionnaire, (2024)). The responses indicate a consensus among technicians on most questions. For instance, regarding ergonomic challenges highlighted in question 3, one technician mentioned, "*Wind turbines are often not ergonomically designed, lacking laydown areas for bags and equipment, leading to obstacles and potential hazards. Restricted access, working in areas with significant grease or oil, and maintaining a clean environment pose substantial challenges.*" Another respondent highlighted the absence of adequate sanitary facilities for women on WTs.

A detailed analysis of the survey results suggests that conducting I&M activities on WTs is an exceptionally challenging task, which significantly increases the likelihood of HE. Moreover, the lack of real-time supervision at inspection sites reduces the opportunities to correct such errors. Consequently, the following section introduces a novel framework for a Computer Vision supervisory agent designed to monitor technicians during inspections and capable of raising an alarm if there is a risk of HE

3. COMPUTER VISION-BASED RECOMMENDATION AGENT

The steps involved in the framework that integrates multi-modal inputs like videos and images consist of the following steps:

1. Data Collection: Using high-resolution cameras, we will gather a comprehensive dataset of videos and images capturing expert technicians performing WT inspections.
2. Data Preprocessing: We will apply techniques like frame extraction, noise reduction, and image stabilization to the recorded videos and images to prepare the data for analysis. Next, we will manually annotate them with labels indicating correct and incorrect actions, focusing on key inspection points and common errors. Finally, we will augment the data using techniques such as rotation, scaling, and mirroring to increase the dataset's robustness against variations in real-world scenarios.
3. Model Development: We will use convolutional neural networks (CNNs) to extract features from images and video frames, and employ Long Short-Term Memory (LSTM) networks to analyze temporal dependencies in video data. We will then implement a fusion technique to effectively integrate features from different modalities, capturing a comprehensive profile of inspection activities. Lastly, we will develop a classification system using machine learning to distinguish between correct and incorrect inspection behaviors based on the labeled data.
4. Real-Time Monitoring System: We will install a monitoring device at strategic locations around the wind turbine. Each device will be equipped with a high-resolution camera and a speaker system. The camera will continuously capture video of the technician's activities, allowing the system to visually monitor the inspection process from multiple angles. We will use edge computing devices integrated within the monitoring systems to process the data in real-time, significantly reducing latency and ensuring that any deviations or anomalies are promptly detected. The speaker will provide immediate audio feedback and recommendations to the technician based on the real-time analysis, including alerts about potential errors, reminders of inspection steps, or safety warnings.
5. Feedback Loop: We will integrate a feedback system where the model learns from new inspection videos over time, adapting to new techniques and evolving standards in turbine maintenance. We will regularly evaluate the system's accuracy and reliability in detecting deviations and making iterative improvements based on real-world performance and feedback from technicians and supervisors. Furthermore, the technicians will also be able to interact with the system using voice commands. They will be able to respond to the audio cues by confirming receipt of messages or asking for further clarification. They will also be able to report issues, fetch information, or even tag certain observations without having to stop their work or remove their gloves, which can be particularly useful in harsh weather conditions.

The deployment of such a framework has the potential to lower the HE significantly within WT maintenance and it also aligns with the broader goals of the wind industry to reduce costs and improve the reliability and efficiency of green energy production. As the industry continues to evolve, the continuous refinement and adoption of such integrated frameworks will be essential for sustaining growth and ensuring the safety and well-being of the human technicians at the heart of these operations.

4. CONCLUSION

This paper laid out the critical importance of integrating HFs into the O&M of WFs, with a particular focus on the potential to enhance safety and efficiency through advanced technologies and methodologies. We discussed various approaches that have been used in the past for performing HRA to estimate HEP. The important PSFs for maintenance activity on WFs, include environmental conditions, ergonomic challenges, organizational aspects, accessibility and logistics due to remote locations, communication and coordination for emergency response, the use of specialized tools, and psychological stressors. A questionnaire was designed to collect feedback on PSFs from WT technicians. For example, all the technicians agreed that the awkward positions required for accessing components like blade root bolts not only increase the risk of injury but also elevate the likelihood of mishandling equipment and making errors.

To address these issues, we proposed a computer vision-based supervisory agent capable of real-time monitoring. This system, which utilizes multi-modal inputs from high-resolution cameras and provides audio feedback, represents a significant leap forward in reducing HE. By continuously capturing and analyzing the technician's actions, the system offers corrective feedback and actionable recommendations, thereby ensuring adherence to best practices and enhancing overall safety.

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BIOGRAPHIES

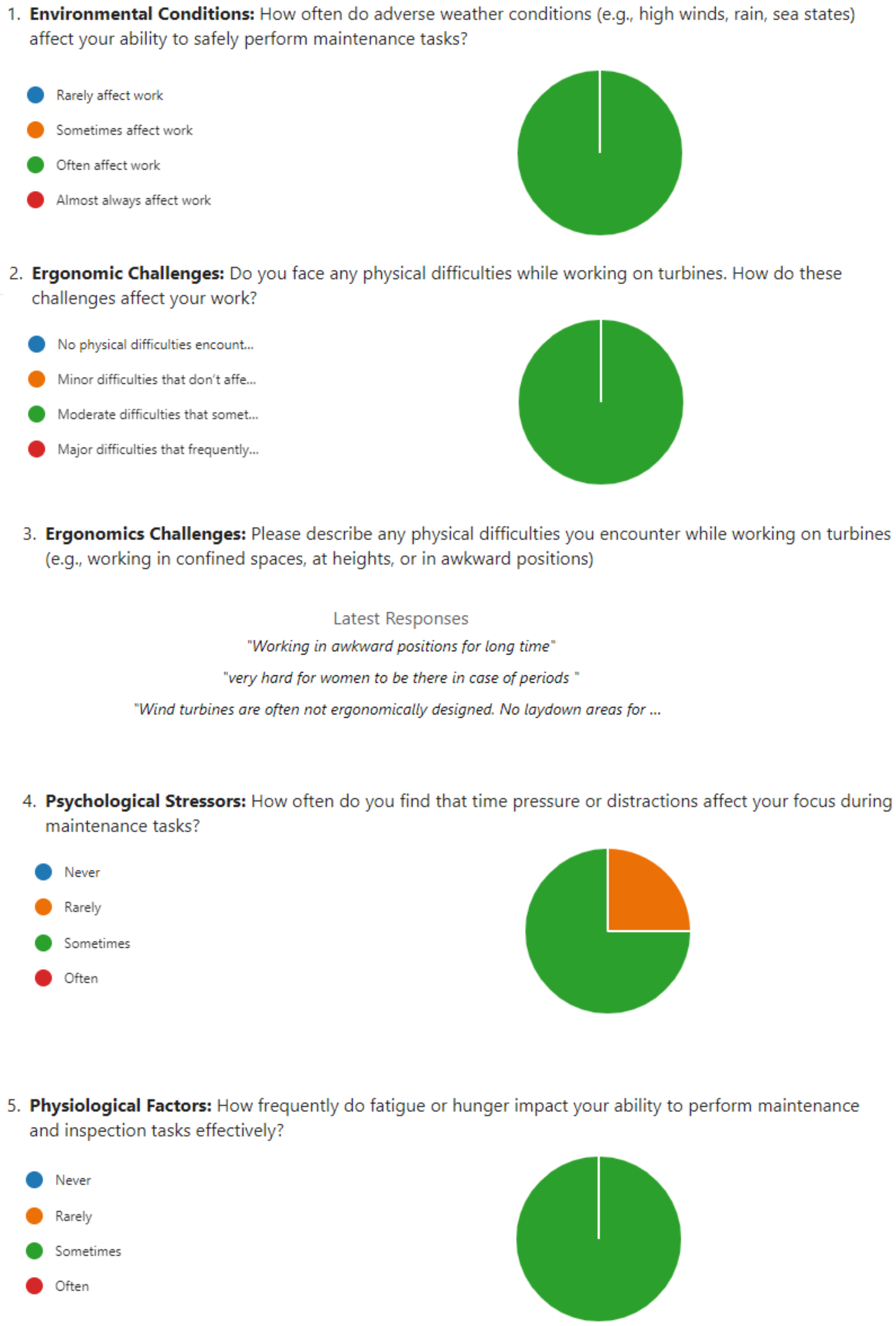
Arvind Keprate received his B. Tech in Mechanical Engineering (2007) from Himachal Pradesh University, M.Sc. in Marine & Subsea Technology (2014), and PhD (2017), in Offshore Engineering from the University of Stavanger, Norway. He is currently a Professor at Oslo Metropolitan University where he teaches Design related courses to Mechanical Engineering students. Besides this, he also teaches Machine Learning, Probability & Statistics at Kristiania University College in Oslo. He has been a visiting researcher at the Prognostics Center of Excellence, NASA Ames Research Center, USA. Currently, his research is focused on Digital Twins and PHM of complex Socio-Ecological-Technical Energy Systems such as Wind Farms.

Stine Skaufel Kilskar has an M.Sc. in Industrial Economics and Technology Management (2014) from the Norwegian University of Science and Technology, Norway, with a focus on strategic change management. She is currently a Research Scientist at SINTEF Digital in Trondheim. She has ten years' experience of working in safety-related research projects within various industries, such as construction, maritime, oil & gas, and energy. The research is mainly focused on safety management and human factors.

Pete Andrews qualified from the University of Sheffield with a Masters degree in Aerospace Engineering in 2005. Working within the power industry for the last 19 years he has delivered operational, engineering and leadership roles across a broad range of power generation assets and technologies. Previously he delivered a number of roles within leading utilities including Commercial Manager supporting major asset divestments and managing offshore wind services and Plant Manager accountable for a large offshore wind farm. Recognizing that the pace of innovation in offshore wind operations and maintenance was lagging compared to the rate of development in other aspects of the sector he founded EchoBolt, an organisation dedicated to deploying advanced technologies to improve the management of structural integrity of wind turbines.

Appendix

Fig 3. Response of Questionnaire



1. **Environmental Conditions:** How often do adverse weather conditions (e.g., high winds, rain, sea states) affect your ability to safely perform maintenance tasks?

2. **Ergonomic Challenges:** Do you face any physical difficulties while working on turbines. How do these challenges affect your work?

3. **Ergonomics Challenges:** Please describe any physical difficulties you encounter while working on turbines (e.g., working in confined spaces, at heights, or in awkward positions)

Latest Responses

"Working in awkward positions for long time"

"very hard for women to be there in case of periods "

"Wind turbines are often not ergonomically designed. No laydown areas for ...

4. **Psychological Stressors:** How often do you find that time pressure or distractions affect your focus during maintenance tasks?

5. **Physiological Factors:** How frequently do fatigue or hunger impact your ability to perform maintenance and inspection tasks effectively?

6. **Organizational Support:** How adequate do you find the training and resources provided for dealing with the specific challenges of offshore wind turbine maintenance?

7. **Technical Complexity:** Rate the level of difficulty you face in understanding and applying the technical knowledge required for turbine maintenance.

8. **Accessibility and Logistics:** How do the logistics and accessibility of offshore wind farms impact your maintenance work, particularly in emergency situations?

9. **Communication and Coordination:** Evaluate the effectiveness of communication within your team and with management, especially for coordinating maintenance activities and responding to incidents.

10. **Safety and Emergency Procedures:** How confident are you in the safety protocols and emergency response plans in place for offshore wind turbine operations? Have you identified any areas for improvement?