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Review

Enhancing Offshore Wind Turbine Integrity Management: A Bibliometric Analysis of Structural Health Monitoring, Digital Twins, and Risk-Based Inspection

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Abstract: The grand challenge of sustainable development, increased demands for resilient critical infrastructure systems, and cost efficiency calls for thinking and acting "out of the box". We must strive to search for, identify, and utilize new and emerging technologies and new combinations of existing technologies that have the potential to improve present best practices. In integrity management of, e.g., bridge, offshore, and marine structures, relatively new technologies have shown substantial potentials for improvements that not least concern structural health monitoring (SHM), digital twin (DT)-based structural and mechanical modeling, and risk-based inspection (RBI) and maintenance planning (RBI). The motivation for the present paper is to investigate and document to what extent such technologies in isolation or jointly might have the potential to improve best practices for integrity management of offshore wind turbine structures. In this pursuit, the present paper conducts a comprehensive bibliometric analysis to explore the current landscape of advanced technologies within the offshore wind turbine industry suitable for integrity management. It examines the integration of these technologies into future best practices, taking into account normative factors like risk, resilience, and sustainability. Through this analysis, the study sheds light on current research trends and the degree to which normative considerations influence the application of RBI, SHM, and DT, either individually or in combination. This paper outlines the methodology used in the bibliometric study, including database selection and search term criteria. The results are presented through graphical representations and summarized key findings, offering valuable insights to inform and enhance industry practices. These key findings are condensed into a road map for future research and development, aimed at improving current best practices by defining a series of projects to be undertaken.

Keywords: integrity management; offshore wind turbines; risk-based inspection; digital twin; structural health monitoring; bibliometric study; road map

Academic Editor: Davide Astolfi

Received: 25 November 2024
Revised: 23 January 2025
Accepted: 25 January 2025
Published: 1 February 2025

Citation: Bull, T.; Liu, M.; Nielsen, L.; Faber, M.H. Enhancing Offshore Wind Turbine Integrity Management: A Bibliometric Analysis of Structural Health Monitoring, Digital Twins, and Risk-Based Inspection. *Energies* **2025**, *18*, 681. https://doi.org/10.3390/en18030681

1. Introduction

Renewable energy sources are essential for reducing carbon dioxide emissions and ensuring future energy security. Offshore wind energy is one of the most promising solutions and the European Union's current ambition is to install 300 GW of offshore wind capacity by 2050 [1], a significant increase from the 19 GW installed in 2023 [2]. The components of offshore wind turbines (OWTs) are susceptible to harsh met-ocean conditions, and offshore wind farms (OWFs) are located far from shore, making maintenance both difficult and costly with approximately 25% of the OWF cost being used on Operation and Maintenance (O&M) activities [3,4]. The O&M activities can be split into operations, planned maintenance, and unplanned maintenance, where unplanned maintenance can contribute to 90% of the total O&M costs [4]. Researchers are therefore proposing various O&M strategies for OWFs to reduce unplanned maintenance costs and optimize the maintenance strategies [5–8]. The unplanned maintenance costs typically arise in cases of component failures (corrective maintenance). The benefit of moving to predictive maintenance to reduce the unplanned maintenance costs is evident [9–11]. The cyclical nature of dynamic operational and environmental stresses poses a risk of fatigue-induced cracks in welded details such that it is imperative to establish robust Structural Integrity Management (SIM) protocols for optimization of the O&M [12,13]. Traditionally, in offshore wind energy, SIM involves periodic inspection of critical components and predefined decision protocols for addressing detected cracks. However, this conventional approach, while prevalent in most certification standards, can be notably enhanced by transitioning to risk-based inspection (RBI) procedures. Advancements in sensor technologies pave the way for enhancing RBI procedures with the latest developments in structural health monitoring (SHM) and digital twin (DT) methods. SHM provides real-time monitoring of structural performance, facilitating early detection of damage and structural identification. DTs are virtual replicas of OWFs and incorporate SHM data to predict future degradation and support decision-making on integrity management. The integration of RBI with SHM and DT has the potential to effectively tackle the unique challenges of integrity management of OWFs. A brief description of each of the technologies and their combinations is provided in the following.

Risk-based inspection enhances safety and minimizes maintenance costs by prioritizing inspections on the most critical details of a structure or system. Its foundation, laid over 50 years ago with Bayesian decision analysis [14,15], was first applied in the offshore oil and gas (O&G) industry to manage fatigue crack growth in steel jacket structures [16,17]. Initially focused on fatigue-sensitive details, RBI later evolved to encompass structural system approaches [18–20]. By the late 1990s, RBI practices for steel jackets stabilized and expanded to Floating Production Storage and Offloading (FPSO) units and Floating Storage and Offloading (FSO) units [21,22]. Despite these advances, the complexity of RBI limited its wider adoption until the development of generic schemes that facilitated optimal inspection plans using standard offshore design variables [23].

The benefits of RBI are quite significant—especially in terms of safety and reduced operating expenses (OPEXs) and capital expenditures (CAPEXs)—but also in terms of more consistent and transparent safety and reliability management. During recent years, risk-informed integrity management has been developed further and by now is available not only for particular details in individual structures or structural systems but more generally for portfolios of facilities comprised by structural systems and mechanical and electrical systems [24]. Moreover, besides risk information, the most recent frameworks also address resilience and thus embed the aspects of organizational capacity and the functionality of technical systems in the overall integrity management philosophy. Input to RBI is conventionally obtained from simulation by digital models of the components in question based on conservative design model assumptions. These modeling assumptions can be updated to create a so-called DT [25,26].

The digital twin as a decision-making tool in asset management is well established and has been successfully implemented across various industries. Its first application dates back to NASA's Apollo program in 1960 [27]. Since then, DT technology has been adopted in aerospace engineering, automotive and bridge engineering, and offshore structures [28–31].

Currently, the potential of DT technology is being explored in the offshore wind industry, primarily at the feasibility and conceptual levels [32–37].

The calibration schemes of DTs can be split into two areas, namely Bayesian-based and sensitivity-based. The sensitivity-based models are deterministic methods and employ an iterative process to minimize the residuals between measured and model-predicted responses using a weighted least-squares approach. The first encounters of sensitivity-based model updating based on modal analysis dates back to the early 1970s [38–40]. On the other hand, the Bayesian-based methods are more computationally demanding when updating prior distributions to posterior distributions based on the likelihood obtained from measurement data. The application of Bayesian methods in model updating gained attention primarily due to the work of Beck and Katafygiotis [41]. Bayesian methods have been in use for at least 20 fewer years, likely due to the high computational demands required, which were a limitation in the early stages of their adoption. Both calibration methods conventionally apply features extracted from measurements on the actual structure in operation by using SHM or condition monitoring (CM) systems [42,43].

Structural health monitoring was first used for aircraft damage detection in aerospace engineering [44,45]. In the late 1970s, its use expanded to offshore platforms [46], and by the early 1990s, it included civil engineering and infrastructure [44,47]. In the past two decades, advancements in sensor technology have greatly expanded SHM, allowing for feasible measurements of strain, acceleration, and temperature. SHM is viewed as an inverse problem, identifying structural defects through data analysis, with Rytter in 1993 [48,49] providing a four-tier classification for damage identification. SHM for damage identification can be divided into two main approaches: data-driven and model-driven. Although data-driven SHM has advanced significantly, it faces limitations, such as reliance on large volumes of high-quality data and vulnerability to noise, environmental changes, and operational shifts [50,51]. These methods often struggle with higher-level damage classification due to their training on specific datasets, leading to reduced robustness in unfamiliar scenarios [46,47,52]. To overcome these limitations, model-driven approaches that involve a numerical representation of the system (DT) are essential. The potential of SHM and the value of information (VoI) have been demonstrated for various structural systems such as wind turbine structures through cost–benefit analyses [34,53–57]. The VoI showcases that SHM offers a compelling and cost-effective method for both the design of new and for the assessment of offshore assets that are facing lifetime extension—beyond what current methodologies can provide.

To summarize, the current best practice of RBI in the O&G industry can be directly transferred to the offshore wind industry for optimizing inspection planning. However, these practices can be further enhanced through the integration of available research technologies such as DTs and SHM. Furthermore, incorporating normative considerations like resilience, risk, and sustainability into integrity management can be effectively achieved through the integration of SHM, DTs, and RBI. SHM systems provide continuous real-time data on the condition of structures, enhancing resilience by enabling timely interventions and predictive maintenance. When combined with DTs, which create a virtual replica of the physical asset, this approach allows for proactive identification and resolution of potential issues. RBI further strengthens risk management by prioritizing inspection and maintenance activities based on the likelihood and consequences of failure, informed by SHM data and DT simulations, which minimizes unexpected failures and enhances safety. Additionally, the integration of these technologies supports sustainability by optimizing maintenance schedules, reducing unnecessary inspections, and minimizing environmental impact through efficient resource use. By systematically incorporating these normative considerations, SHM, DTs, and RBI contribute to more resilient, risk-informed, and sustainable integrity management practices.

The present paper therefore presents a state-of-the-art bibliometric study serving as the basis for a road map development of an optimal approach for risk- and resilience-informed integrity management for wind turbine facilities at the level of offshore wind turbine parks. The road map development provided in Section 4 shows how implementation of SHM, DT and RBI technologies may be realized in practice—and thus significantly push the frontier of technological developments towards the urgently needed new paradigm towards sustainable management of the built environment addressed in [58].

Section 2 provides details on the methodology used to delimitate the relevant problem context, including query strategy, followed by a visualization and discussion of the results in Section 3. Section 4 presents a summary of the conclusions, together with an outline for the road map for implementation.

2. Methodology

In mapping the state of the art, relevant search terms for each of the three technologies (RBI, DTs, and SHM) are identified within the context of normative decision-making for offshore wind. The search terms are described in Section 2.1 and the derived number of research publications from an online database are described in Section 2.2. The results are subsequently visualized and analyzed in Section 3. A flowchart of the approach is provided in Figure 1.

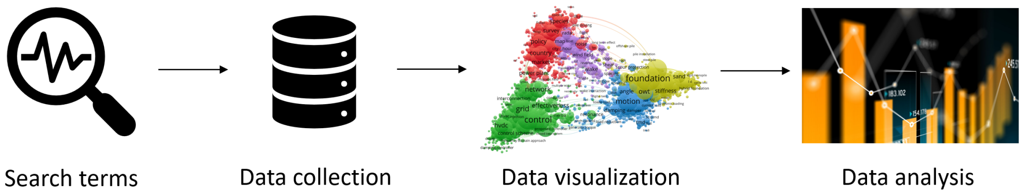


Figure 1. Workflow of the approach for the bibliometric study.

2.1. Search Terms

The aim of this paper is to explore the current landscape of advanced technologies in the offshore wind turbine industry, with a focus on their suitability for integrity management. This exploration highlights current research trends and examines the extent to which normative considerations influence the application of RBI, SHM, and DTs, either individually or in combination, within the offshore wind sector.

A total of five groups of search terms have been established, where the first two are within the application context of offshore wind turbine energy systems and normative decision-making. The last three groups are search terms related to the technologies.

1. Offshore wind energy: *"offshore wind"* The first group targets the broad context of offshore wind energy systems. The results offer an overview of the evolution and current state of knowledge in offshore wind energy. When combined with terms from Groups 2–5, they help delineate the theoretical, methodological, and technological advancements in offshore wind energy applications, highlighting trends over time, geographic areas, and key research and development (R&D) actors.
2. Normative decision-making: *"reliability" OR "risk" OR "resilience" OR "resilient" OR "sustainability" OR "sustainable"*
   This group contains search terms related to normative decision-making and is exclusively used in combination with other groups, i.e., these search terms are not queried

individually from the database. The results provide insights into available knowledge regarding strategic and operational planning, governance, and regulation at both pre-normative and normative levels.

3. Risk-based inspection planning: *("integrity management" AND "reliability") OR "risk based inspection" OR "risk-based inspection" OR "reliability based inspection" OR "reliability-based inspection"*
   The third group of search terms pertains to the methodology of RBI for optimal integrity management. The results deliver a general overview of theoretical, methodological, and technological advancements over time, across various geographic regions, and by different R&D contributors.
4. Structural health monitoring: *"structural health monitoring" OR ("condition monitoring" AND "structure") OR (condition monitoring" AND "structures") OR ("condition monitoring AND "structural") OR "SCADA" OR "structural damage detection"*
   The search terms of the fourth group focus on the process of SHM during the operation and maintenance phases of a structure's life-cycle. The results offer detailed information on theoretical, methodological, and technological developments over time, geographic distribution, and key R&D actors.
5. Digital twin technology: *"digital twin" OR "digital twins"*
   The search terms of this group relate to DT technology, covering both modeling and application aspects. The results provide comprehensive information on theoretical and methodological advancements over time, across different regions, and by various R&D actors. These data can be used comparatively to assess the transferability of digital twin technology across diverse applications.

2.2. Data Collection

The Web of Science (WoS) database was selected to extract records for the bibliometric state-of-the-art study. The WoS database was chosen over other databases due to its extensive long-term coverage within the field of engineering and natural sciences. In addition, there is a large overlap with the similar Scopus database [59,60]. The WoS database is known to have bias towards English-language research; however, this is not found influential for the present bibliometric study [61]. The resulting groups of search terms are organized into various combined queries to facilitate contextual understanding of the state of the art in the above three technologies, as well as the level of integration among them. The search terms for each group, together with the query results from the WoS database, are provided in Figure 2. n_x in the figure describes the number of query results within a specific group combination x, e.g., $n_{1,2}$ refers to the query results from Groups 1 and 2.

There are a number of conclusions that can be drawn already from these query results. Of the three technologies, research on SHM yields by far more results than research on RBI and DT both with and without the contexts included in the queries. There is no research that integrates all the aspects, which testifies to the novelty of R&D initiatives on the addressed technologies. Even when not incorporating the normative context of risk, resilience, and sustainability as a criteria in the literature search, there is still no research combining the three investigated technologies in the application context of offshore wind energy. There is very limited research where partial integration of the three technologies is manifested in the offshore and normative contexts. Integration of the three technologies with and without context in the form of normative decision-making leads to the same number of paper hits, with only three sources found. Thus, a significant potential in offshore wind energy is present for optimal decision-making based on the three technologies.

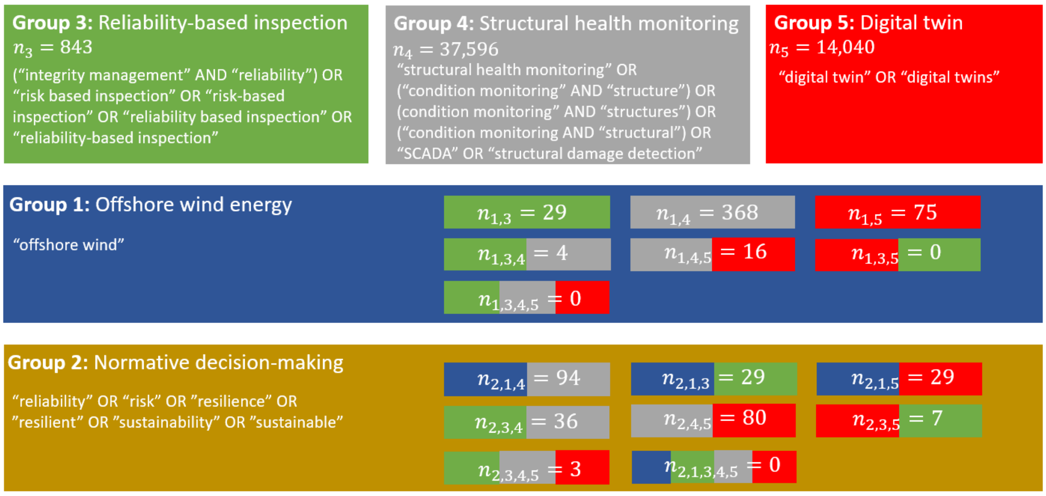


Figure 2. Group names along with the associated search terms and query results.

2.3. Bibliometric Networks in Research Visualization

The VOSviewer software (version 1.6.20) is used to illustrate the query results from the WoS database with bibliometric networks. VOSviewer is a text-mining software application, which performs part-of-speech tagging and uses a filter to identify noun phrases (terms), for which a relevance score is calculated. Terms are derived from the titles and abstracts of the records downloaded from the WoS and are in plots represented by their label and a circle [62]. Bibliometric networks are essential tools for visualizing bibliometric research, consisting of nodes and edges. Nodes represent elements such as research fields, publications, journals, researchers, or keywords, while edges signify relationships between these nodes. This study employs two types of bibliometric networks, term co-occurrence networks and bibliographic coupling networks, to explore and analyze research patterns and connections.

Term co-occurrence networks, constructed using VOSviewer, reveal relationships among topics within a research field, helping to identify potential research gaps. VOSviewer extracts relevant terms from titles, abstracts, and keywords using text-mining techniques. These terms are then analyzed to generate a co-occurrence network. In these networks, nodes represent terms, and edges indicate the co-occurrence relationships between them. The size of a node corresponds to the number of publications containing the term, and edges' thickness reflects the strength of the co-occurrence. The binary counting method is used, treating a term's presence or absence equally, regardless of frequency. Network visualizations display terms and their relationships. Terms that frequently co-occur are placed closer together, forming clusters. Each cluster, represented by a unique color, highlights related terms, indicating distinct research areas.

Bibliographic coupling networks, also constructed using VOSviewer, focus on institutions to analyze global research distribution and collaborations. These networks show the relatedness of items based on shared references. The more references two items share, the stronger their bibliographic coupling. Fractional counting is used to balance the weight of links, mitigating the impact of highly cited publications or those with extensive reference lists. Density visualizations for authors highlight knowledge hubs and subject experts, using a color gradient to represent author density. Network visualizations for countries illustrate research contributions and collaborations, with node size indicating importance and edge strength reflecting the number of shared references.

Both term co-occurrence and bibliographic coupling networks provide valuable insights into research trends, knowledge distribution, and collaboration patterns, supporting the identification of research gaps and the advancement of knowledge within the field. Detailed information on the construction of these networks is provided in the following sections.

3. Visualization and Data Analysis

Figure 3 illustrates the historical evolution and research volume concerning the three investigated technologies of DTs, RBI, and SHM. Note that the y-scale is in logarithmic scale. From Figure 3, it can be observed that the research in DT and SHM started around the same period in 1973. The research on RBI started at a later stage in 1990 but has had a consistent number of publications since 1990, which is similar for the SHM research (but with higher attention). The DT research attention, on the other hand, had close to no research attention until 2014, when the attention and hype around DTs increased significantly with an exponential growth in the publication counts.

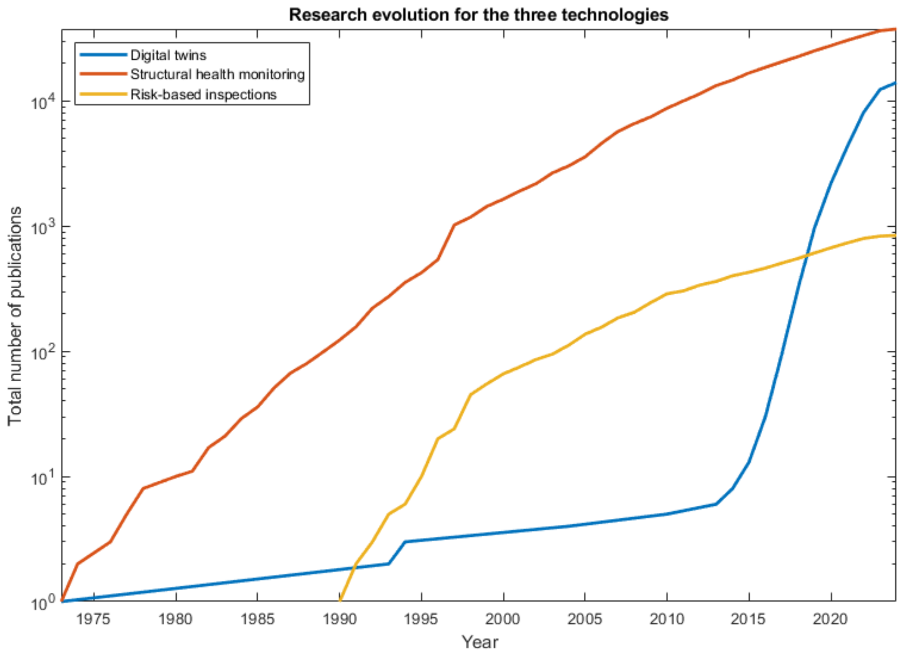


Figure 3. Research evolution for the three technologies of DTs, RBI, and SHM.

Even with the exponential growth in the DT publications, almost no research is within offshore wind energy (75 publications), normative decision-making (29 publications), and a combination of both (3 publications); see Figure 2. Normative decision-making is required for the translation of the knowledge obtained from the DT into practical applications in a decision process.

3.1. Term Co-Occurrence Analysis Results

The network visualization for Group 1 (offshore wind energy) is provided in Figure 4, where a total of three clusters is generated.

It is observed from the network visualization that publications are clustered around the electrical system (blue), environmental assessment (green), and structural design (red). The link between the three clusters is very weak, which is an indication of the lack of integration between the different fields. This lack of integration between the fields can be problematic, as, e.g., the control strategy of the wind turbine (located in the electrical system group) significantly impacts the structural stress levels (located in the structural design group). By tweaking the control system to reduce the structural system, stress could provide additional benefits and prolong the lifetime of the OWT. There is low focus on the O&M of the wind turbines as fatigue, risk, and reliability are almost non-existent. The focus is primarily on design and modeling of the loads and soil behavior. This indicates that there is a focus on the capital expenditure (CAPEX) and not on operating expense (OPEX) in the offshore wind turbine industry. To reduce the levelized cost of electricity (LCOE) of offshore wind, both CAPEX and OPEX should be in focus, such that an optimum can be found between the two. A higher CAPEX can lead to a lower OPEX and vice versa. A set of network visualizations will be provided in the following for each of the technologies with and without the context of offshore wind.

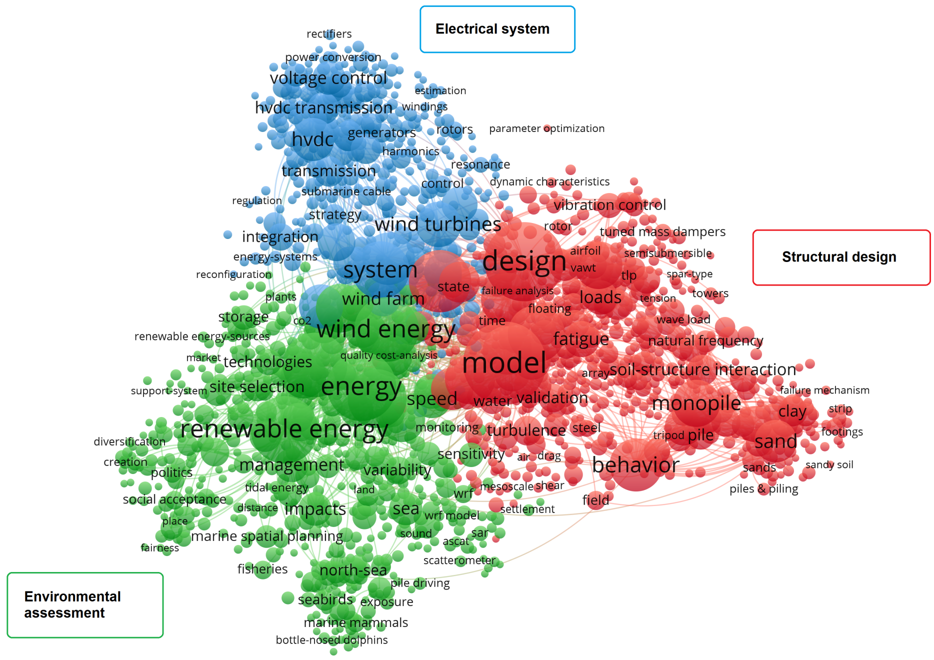
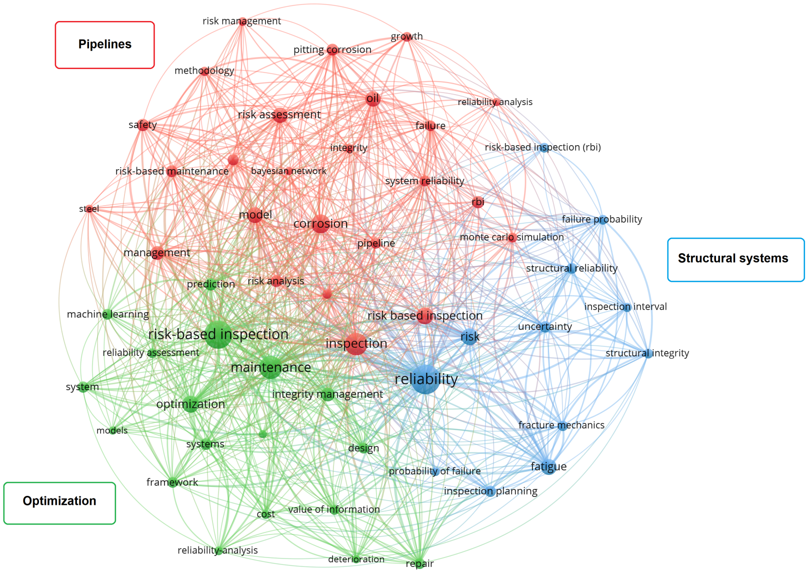


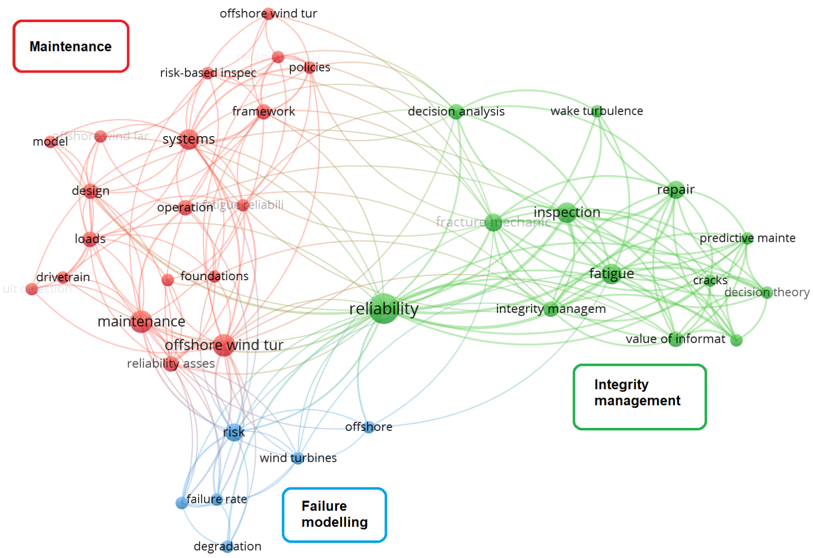
Figure 4. Network visualization for Group 1 (offshore wind).

From the network visualization in Figure 5a (Group 3 RBI), it is observed that most of the applications of RBI are in the area of O&G (for pipelines and structural systems), while not too much research is related to the wind energy domain. O&G is the preceding field and the operators are therefore more experienced within efficient integrity management, which is why a transfer of best practice from O&G to offshore wind is needed. This observation also verifies problem statement 5. It appears that in the context of RBI, only cost is taken into account, whereas terms related to benefits, resilience, or sustainability are not apparent from the bibliometric study. Both resilience and sustainability are normative concepts related to risk. Indeed, it could be argued that the frontier reason for developing and using offshore energy is the consideration that it is a benefit expressed as the desired outcome of sustainability. The normative concepts of resilience and sustainability are directly related to the RBI framework but appear to remain unexploited in the literature.

When looking at Figure 5b, with RBI in the offshore wind context, the split is within the RBI areas of maintenance, integrity management, and failure modeling in the form of fatigue degradation models. The research is very limited and seems to only focus on the early stages of implementation with the value of information. The focus is on both the foundation structures and the drive train of the wind turbine, which indicates that there is an equal focus on both mechanical systems and structural systems.



(**a**) Group 3 (RBI)

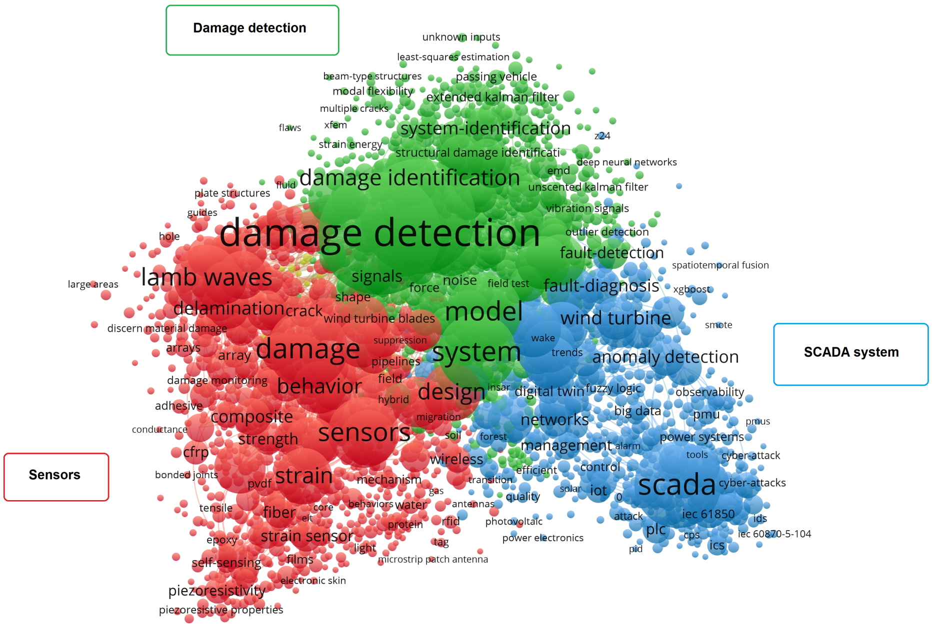


(**b**) Group 1 (offshore wind) and Group 3 (RBI)

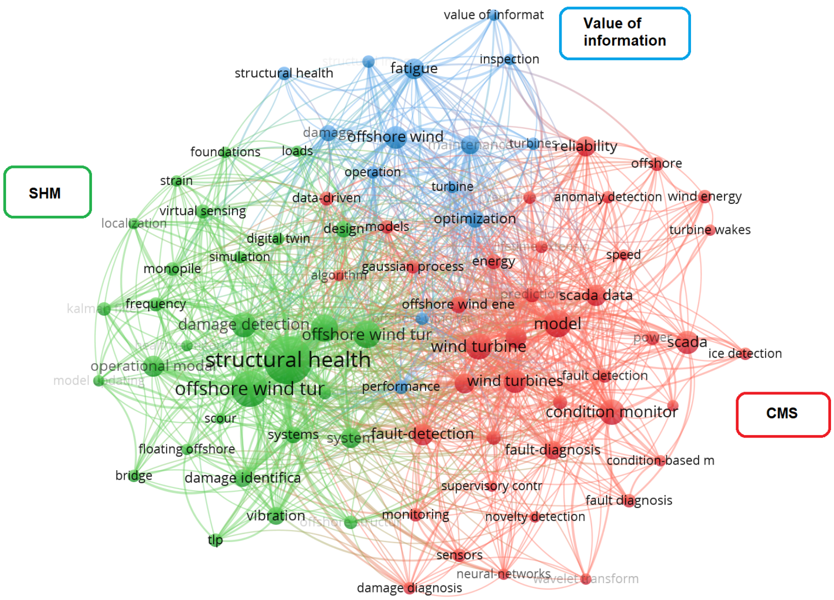
Figure 5. Network maps for RBI with and without offshore wind.

The SHM group search term, with the network visualization in Figure 6a, addresses both SHM of structural components and CMS of mechanical components. The SHM clusterings are split in three clusters, with a focus on damage detection, sensors, and SCADA systems. The damage detection part is focused on structural components with search terms such as system identification, Kalman filters, vibrational signals, and models. The SCADA system group is primarily focused on control and anormaly detection in the wind turbine operational system, while the sensor group focuses on the structural and mechanical components based on strain and accelerometer sensors. When adding the context of offshore wind, research related to both parts appears, while when further adding the context of RBI, only structural health monitoring appears. This indicates that in the context of offshore wind, condition monitoring, which is a mature technique, still has not been applied in support of RBI. This furthermore implies that the joint consideration of SHM and CMS should be investigated in further research.

When combining the SHM terms with offshore wind terms, Figure 6b indicates that the research is mainly split between SHM and CMS. The value of information with subcomponents such as fatigue and optimization highlights a small research area around risk and reliability mostly for CMS. It is therefore very disconnected from the digital twin terms, which are located in the green SHM part with structural components. However, SHM has some integration between both of the other technologies (DTs and RBI), though it can be seen from Figure 2 that no research integrates all technologies at the same time.



(**a**) Group 4 (SHM)

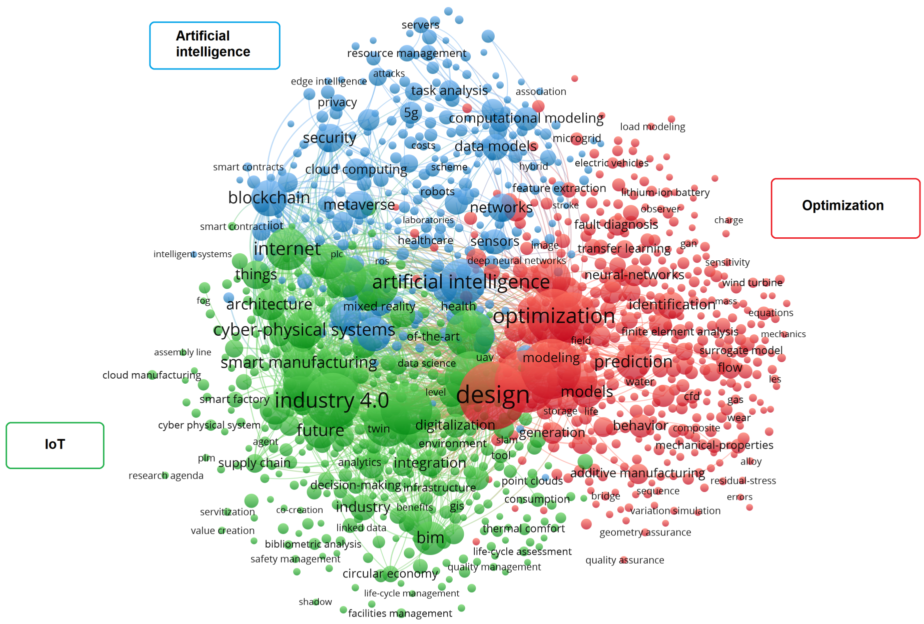


(**b**) Group 1 (offshore wind) and Group 4 (SHM)

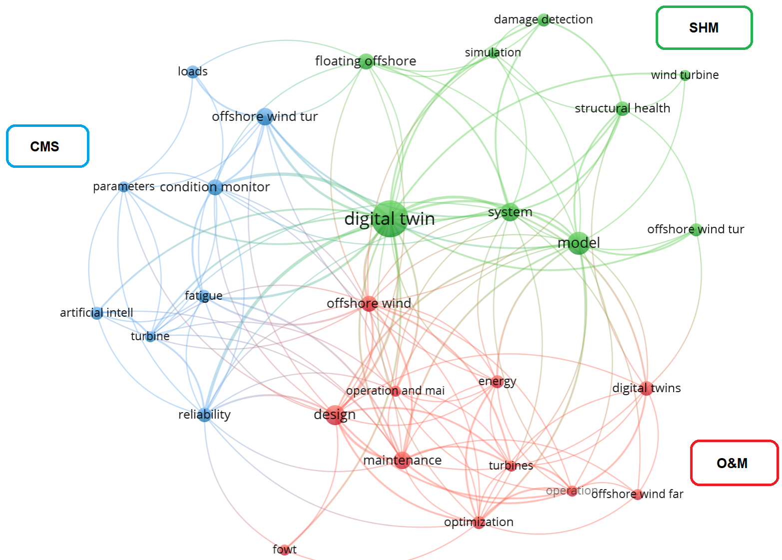
Figure 6. Network maps for SHM with and without offshore wind.

The network visualization for Group 5 is provided in Figure 7a (DT) with three clusters. It appears that there are many possible application domains for DT technology within artificial intelligence (AI), Internet of Things (IoT), and optimization and fault diagnosis. AI focuses on computational areas such as blockchain, cloud computing, metaverse, etc., while IoT focuses on data science, software architecture, and integration of DTs in industry processes. Finally, the red cluster (optimization) uses DTs for fault diagnosis and predictive quantities. This is where the research on offshore wind and normative decision-making is located.

Combining DT search terms with offshore wind search terms only gives 75 papers out of 14,040 papers, with the network illustrated in Figure 7b. The DT usage is evenly split between SHM and CMS (blue cluster). There are no search terms for normative decision-making within the SHM field but only within the CMS field. This indicates that DTs are not yet used within SHM for management activities and lack the maturity to transition from purely modeling quantities to being a decision tool.



(**a**) Group 5 (DT)



(**b**) Group 1 (offshore wind) and Group 5 (DT)

Figure 7. Network maps for DT with and without offshore wind.

Integration of the three technologies without context and with normative context provides the same number of paper hits, with only three publications; see Figure 8 for the network visualization. The focus areas of the papers are split in two, with one being focused on wave load calibration, modal expansion, and machine learning in the context of digital twins. The focus area of the second part is structural monitoring, structural integrity, and risk-based inspections. This indicates that there is some research combining the three technologies. The three publications focus on the early stages of implementation with illustrative numerical examples of a proposed framework in [63], with avenues for future R&D; the concept of digital twins for fatigue assessments in [64]; and a state-of-the-art review of company-specific developments in [65], with future R&D directions towards the combination of SHM, DTs, and RBI.

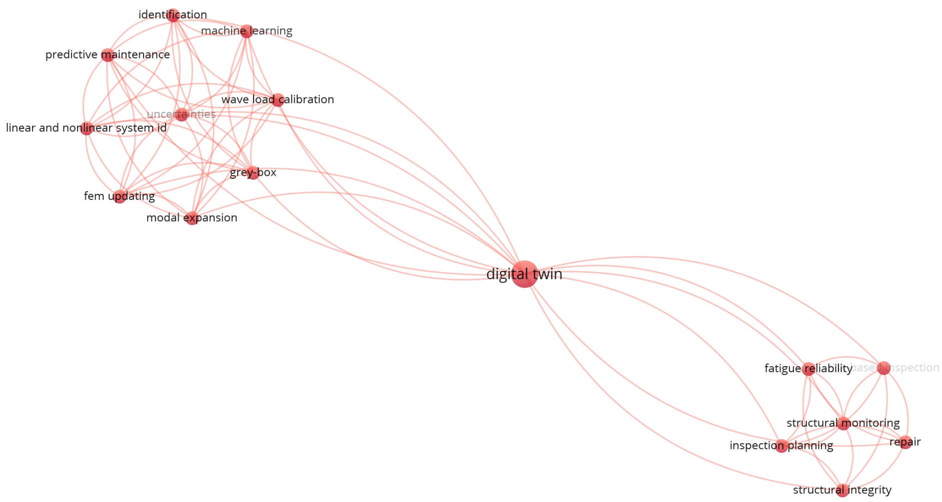


Figure 8. Network visualization for Groups 2 (normative decision-making), 3 (RBI), 4 (SHM), and 5 (DT).

However, introducing the offshore wind context yields no publications, meaning that the transition towards offshore wind is not a focus of the research community.

3.2. Bibliographic Coupling Analysis Results

In this section, the final results from the bibliometric analysis are presented, focusing on bibliographic coupling. Bibliographic coupling networks are utilized to illustrate the distribution of knowledge among countries for the development of the different technologies. The network reveals valuable insights into global research dynamics. It identifies strong international research collaborations, highlighting which countries frequently work together. This analysis also uncovers the volume of research output from different countries and their interconnections through shared references. By examining bibliographic coupling strength, one can discover which countries are leading in specific research fields and track emerging research trends. This facilitates understanding how different countries contribute to the advancement of knowledge in various domains and helps identify potential partners for future projects. Colors in the bibliographic coupling plots represent different clusters. Each cluster groups items that are more closely related based on their bibliographic coupling strength. While the specific colors do not have inherent meanings, they help visually distinguish between the clusters.

In Figure 9, the bibliographic coupling by country is shown for the first group (offshore wind). The research is dominated by China, who, in general, produces very a large amount of research and is also the dominant region for offshore wind capacity. The next largest are the European countries, where the offshore wind capacity is the highest after China, especially countries such as England, Denmark, and the Netherlands [66]. There is a clear collaboration between almost all parts of the world but with some regional grouping in Asia and Europe.

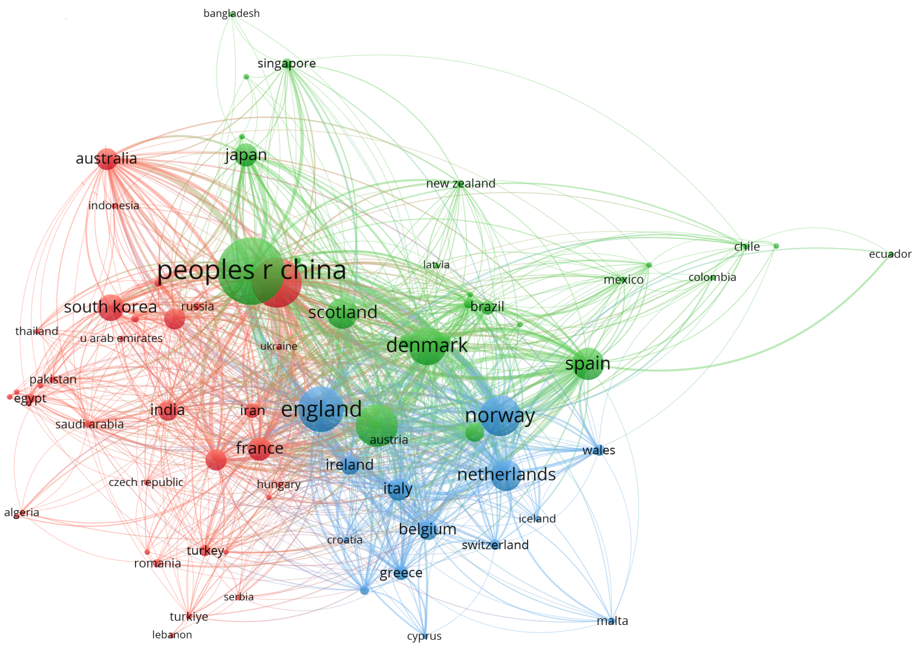


Figure 9. Bibliographic coupling by country of the first group with offshore wind terms.

Figure 10 displays the bibliographic coupling by institution for the third group with search terms for RBI. The dominant producers of research are the USA, Canada, England, and China. The dominant research, as per Figure 5, was in the field of pipelines, where especially the USA is known to have a large track record due to its extensive pipeline network for both CO_2 and natural gas.

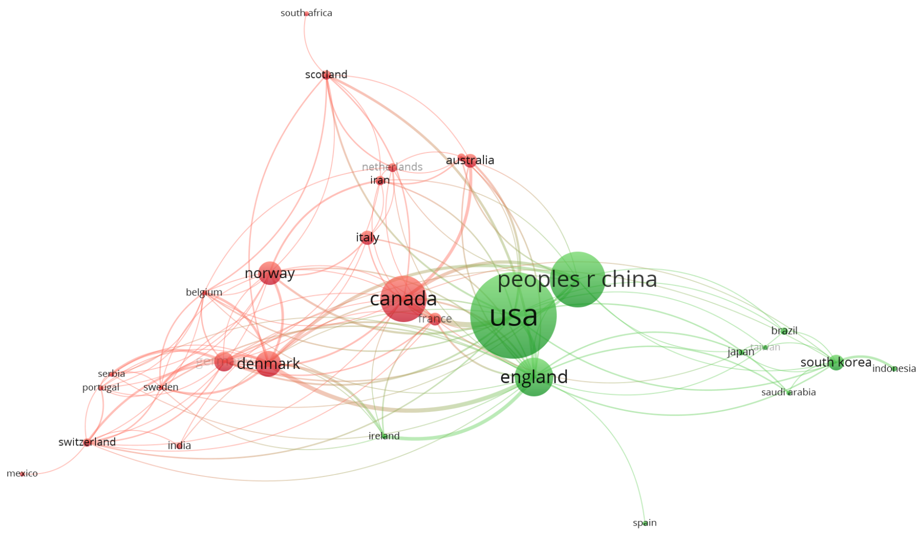


Figure 10. Bibliographic coupling by country of the third group with RBI search terms.

In Figure 11, the bibliographic coupling by institution is shown for the fourth group (SHM). The dominant producers of research are China and the USA, followed by England, Germany, and Italy. The USA has strong links across the map, especially with South Korea and China. China has a very large number of publications but weaker links across the map. The strongest links are between China and the USA.

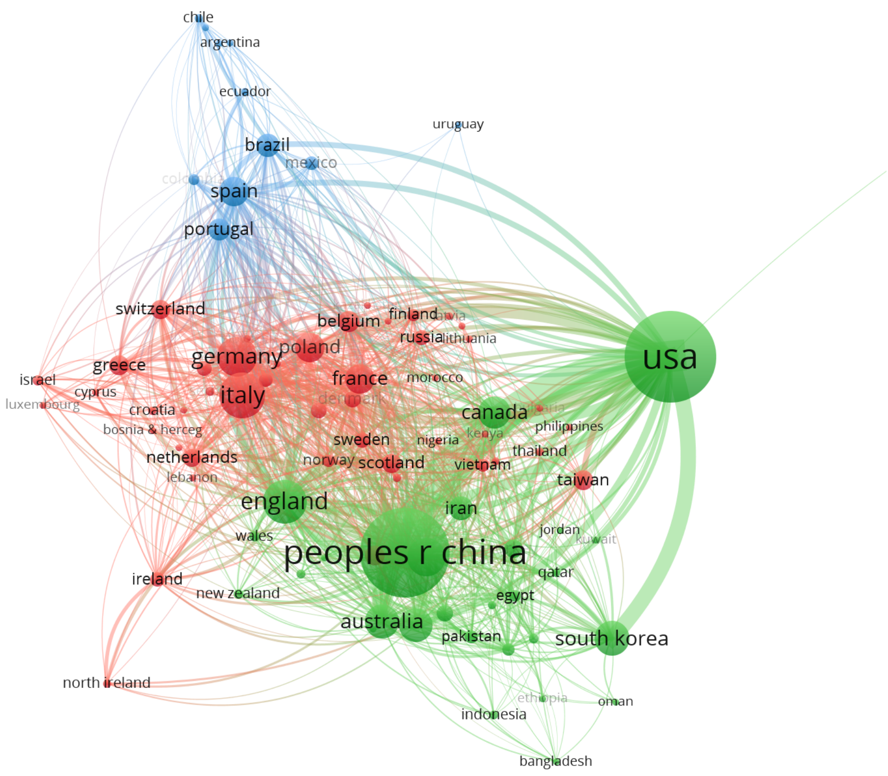


Figure 11. Bibliographic coupling by country of the fourth group with SHM search terms.

Finally, Figure 12 illustrates the bibliographic coupling by institution for the fifth group with search terms for DTs. The dominant producers of research are China, the USA, and Germany. Germany is leading the research in one cluster, while China and the USA have a separate cluster of research with very tight collaboration between America and Asia. The final cluster is relatively small and is driven by Spain, with collaboration links to both of the other clusters.

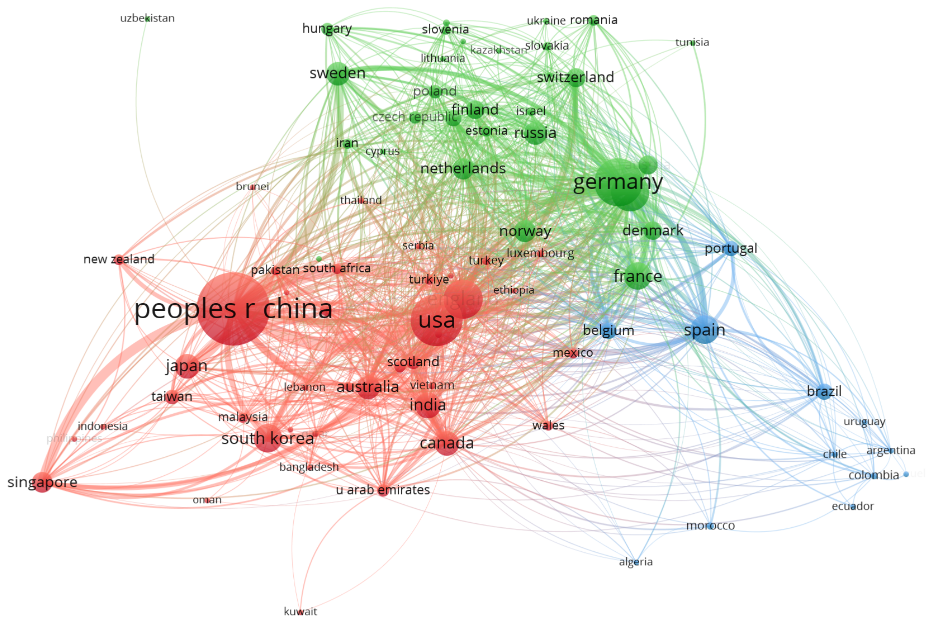


Figure 12. Bibliographic coupling by country of the fifth group with DT search terms.

The geographic distribution of research illustrates the main hubs around research focusing on the three technologies investigated:

- RBI: USA, Canada, England
- SHM: China, USA, England
- DTs: China, USA, and Germany

The USA is conducting significant research in all three areas, but this does not mean that there is a collaboration between the researchers, which can be seen in the lack of integration between the technologies.

4. Conclusions and Road Map

There are latent normative and industrial needs, as well as a significant potential, for enhancing present best practices in the offshore wind turbine industry through the implementation of the technologies of risk-based inspection planning, structural health monitoring, and digital twins individually and especially in conjunction. All three technologies, RBI, SHM, and DTs, have been applied successfully in industrial application areas such as offshore oil and gas exploitation, bridge engineering, and smart cities—but only to a very limited extent in the domain of offshore wind turbine design and integrity management.

With respect to RBI, the theoretical and methodological basis has indeed been transferred from the offshore oil and gas industry to potential application in the wind turbine industry—however, it is still not employed in present best practices. With respect to SHM, the situation is similar. SHM techniques have been, and are being, developed to identify damages developing in the structural and mechanical parts of wind turbine systems, but the utilization of this technology is still not an integral part of design and integrity management best practices.

DT technology applications are emerging in a wide variety of industrial application areas and have been proven to be a very valuable support in understanding structural performance, not least when combined with SHM and utilized during the operational phases of the service lives of structures. There are some initial applications of this technology in the wind turbine industry, but still significant potential for systematic utilization exists.

Most importantly, the combination of the three technologies has tremendous potential for enhancing industrial best practices—both from a normative perspective in pursuit of sustainable development, resilient infrastructure systems, and transparent and risk-informed decision making, as well as from a purely competitive perspective. Namely, the integral application of these technologies has substantial potential for saving material and costs, as well as for enhancing reliability and, in turn, energy production and revenues. Until now, there has been hardly any (or no) research addressing the full integration of RBI, SHM, and DTs, and more developments are needed to achieve this.

Finally, it is observed that in addition to the above-mentioned potentials of adapting and applying RBI, SHM, and DT technologies in the offshore wind turbine industry, there appears to be quite obvious potential for improving present best practices on design and integrity management through the joint consideration of all the individual subsystems of wind turbines. Presently, the design of the individual subsystems of wind turbine structures and mechanical, electrical, and control systems appears to be undertaken in isolation, i.e., individually. This practice obviously does not cater for the potential benefits of joint optimization over possible choices related to the design and integrity management of wind turbines over their life time.

The conclusions of the bibliometric study point to the observation that in the offshore wind industry there appears to be quite obvious potential for improving present best practices on integrity management, which may be realized through (1) joint consideration of all the individual subsystems of wind turbines and wind farms from a system perspective and (2) through a combination of RBI, SHM, and DT technologies. The latter appears to bear tremendous potential for enhancing industrial best practices from a normative perspective in pursuit of sustainable development, resilient infrastructure systems, and transparent and risk-informed decision making. However, in order to achieve this, additional developments and also more research are needed. The following section outlines a road map for implementing the conclusions of the bibliometric study to enhance current industry practices in integrity management while also setting the direction for future research and development.

Road Map for Future Research and Development for Enhancing Best Practice for Integrity Management

Building on the directions outlined by the bibliometric study in this paper and incorporating feedback from key stakeholders such as industry practitioners and certifying agencies (as listed in the acknowledgment section), a road map is proposed for a potential sequence of joint research and development activities—projects—and presented in Figure 13. The road map sets the direction with six projects which should be initiated by industry stakeholders. It should be noted that the road map does not aim to provide details of the activities to be undertaken within the individual projects but is focused on the general objectives and main deliverables to be achieved. The sequence of projects as suggested is logical in terms of what knowledge and methods feed in to which; however, it should be noted that important aspects of the individual projects might be addressed also if the preceding projects have not yet been undertaken.

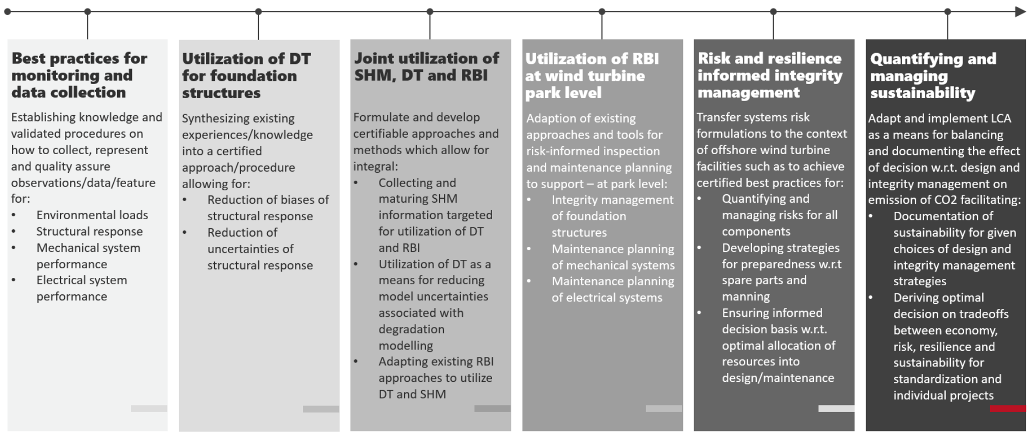


Figure 13. Road map for future developments and research.

The primary focus of the article and the road map is on servicing wind turbines post-commissioning. While we acknowledge that materials and design decisions play a critical role in determining the operational lifespan—especially given the increasing size of offshore wind turbines—this aspect is more relevant to the design phase rather than the integrity management phase. For example, advancements in manufacturing technologies and the development of new materials, such as thicker grades of steel for foundation structures, are indeed vital. However, these aspects are best addressed in a design-oriented context rather than within the scope of the proposed road map. The road map follows current industry practices and standards, such as those defined by DNV, where probabilistic risk-based approaches can be adopted as a means for both lifetime extension and inspection planning for critical details of the support structure [67,68].

The road map presented in Figure 13 serves as input for an envisaged process of joining forces between stakeholders of the wind energy sector, including the industries involved, certification societies, and research institutions, together with monitoring and regulatory (public) authorities.

Author Contributions: Conceptualization, T.B. and M.L.; methodology, T.B., M.L., L.N. and M.H.F.; formal analysis, T.B. and M.L.; writing—original draft preparation, T.B.; writing—review and editing, T.B., M.L., L.N. and M.H.F. All authors have read and agreed to the published version of the manuscript.

Funding: This research is supported by the Ministry of Education and Research under the Knowledge Brokerage Project "Structural Health Management for Offshore Wind Turbine Farms (2021–2022)", facilitated by Energy Cluster Denmark.

Data Availability Statement: The original contributions presented in the study are included in the article, further inquiries can be directed to the corresponding author.

Acknowledgments: The work herein is based on inputs from an Energy Cluster Denmark workshop with participants from industry and academia. The input is highly appreciated for the development of the road map.

Conflicts of Interest: Author Thomas Bull and Michael Havbro Faber were employed by the company NIRAS A/S; Min Liu, Linda Nielsen and Michael Havbro Faber were employed by the company North-Consulting. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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