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Utilizing Continuous Monitoring of Marine Infrastructure and Environment as a Basis for Research Development and Proactive Management

MARIOS KORONIDES[1], PANAGIOTIS STYLIANIDIS[1,2]*, CONSTANTINE MICHAILIDES[3] AND TOULA ONOUFRIOU[1]

[1]Department of Civil Engineering and Geomatics, Cyprus University of Technology, Limassol, Cyprus
[2]Department of Civil Engineering, Neapolis University Pafos, Paphos, Cyprus
[3]Department of Civil Engineering, International Hellenic University, Serres, Greece

Coastal marine areas offer significant potential both for the rapidly growing energy industry and for other public development purposes. As the exploitation of these areas increases significantly, the need for efficient management of infrastructure and environment becomes more important. The work presented in this paper aims to advance proactive solutions for the efficient management of coastal and offshore infrastructure and environment. This is achieved by utilizing the advantages offered by digital technologies. An innovative monitoring system is presented, comprising state-of-the-art sensing equipment installed in two key marine areas of Cyprus, providing real-time monitoring data on structural and environmental parameters. Despite many inherent challenges, the impact of this study is significant in terms of research development, while providing substantial benefits to industry stakeholders. The former is strongly reflected in the advancement of scientific knowledge, and the latter has essential practical importance, highlighting the significance of effective collaboration between the scientific research community and industry. The details of this study along with its impact and prospects are presented and discussed through a series of applications and datasets obtained from the established in-field laboratories.

Keywords: digitization, in-field laboratory, monitoring system, real-time data, sensors, structural parameters

1. INTRODUCTION

Substantial developments in computer-aided design (CAD) (Faux and Pratt, 1979; Li et al., 2005), computer-aided engineering (CAE) (Forbus, 1988; Raphael and Smith, 2003) and building information modelling (BIM) have

*Corresponding author e-mail: p.stylianidis@cut.ac.cy

led to a rapidly growing integrated methodology for the design, construction and management of structural assets. This perspective has been greatly enhanced by recent developments in structural health monitoring (SHM) and structural identification (St-Id) data-driven technologies, which have replaced traditional qualitative and non-continuous monitoring approaches (Li et al., 2014; Çatbaş et al., 2013). Significant progress has also been made in processes of measuring and characterizing environmental conditions and impacts, and in monitoring the operation and process performance of systems. Advanced data-driven technologies and automated systems are now available for real-time monitoring and continuous assessment of the air, soil and water quality status (Artiola et al., 2004; Bayat et al., 2017), allowing conclusions to be drawn about the state of the environment.

Continuous monitoring requires a well-distributed network of sensing devices, which should be properly designed to collect the necessary information in the form of data (Doebelin and Manik, 2007; Huston, 2011). A fundamental component of the process is the provision for data acquisition, transmission and storage (Li et al., 2014; Çatbaş et al., 2013; Huston, 2011). Data acquisition is the process of converting sensor signals into digital values for computer processing applications, which is usually implemented by means of computer programming. Data transfer is implemented through wired technology or wireless communication, a technology area that has seen significant advances over the past few years (Mahmood et al., 2015; Sheng et al., 2015). For the purposes of data storage, different computer data storage models exist, including the emerging cloud storage (Wu et al., 2010) which offers significant advantages as compared to traditional local storage (i.e. physical hardware) models.

To enable features to be extracted from the sensed data, suitable signal processing and signal interpretation techniques have been developed (Amezquita-Sanchez and Adeli, 2016). These techniques rely on probabilistic and statistical tools, capable of exploiting data observations and prior knowledge available to obtain a sufficiently accurate representation of the true characteristics of the problem (Pereyra et al., 2016). Also, research progress in the subject area of artificial intelligence has made it possible to exploit recorded data towards deriving sufficiently accurate identification and prediction models, by means of machine learning and pattern recognition approaches (Sohn et al., 2001; Worden and Manson, 2006; Farrar and Worden, 2013). The recent advances in monitoring system technologies have also given greater value to digital twin technology (Grieves and Vickers, 2017), which mainly aims to improve the structural integrity and life prediction of assets (Wanasinghe et al., 2020a; Pacheco-Blazquez et al., 2024; Taofeeq et al., 2024).

This digital revolution is nowadays transforming many fields in engineering and science. It is widely utilized to improve quality of life, increase productivity, enhance environmental sustainability, and reduce operational costs (Haktanır et al., 2023a). Advanced digital technology is increasingly being used to efficiently manage the concentration of assets and resources, thereby enhancing economic growth, social significance, environmental performance and sustainability (Haktanır et al. 2023b). This concept is largely based on the digital representation of the physical and functional characteristics of assets (i.e. buildings, bridges, roads, railways, ports and other infrastructure) and the interconnection between other services, such as monitoring of environmental conditions, energy consumption, waste management, etc. (Albino et al., 2015; Zanella et al., 2014).

One of the most important fields of application is the management of marine infrastructure and environment. The imperatively growing need to exploit clean energy fuels and renewable energy sources leads to the rapid development of coastal and offshore infrastructure, operations, and processes, as a consequence of the rapidly growing industries of oil and gas, wind power, and solar energy (Al-Rbeawi, 2023; Wanasinghe et al., 2020b; Cao et al., 2022; Kovalnogov et al., 2023; Kou et al., 2022; Elsaraiti and Merabet, 2022). Since the amount of data generated from these applications is now increasing by a large factor, it is becoming extremely important to identify efficient methods for utilizing this data. These methods aim to enhance productivity and efficiency, support maintenance scheduling, eliminate hazardous conditions, mitigate environmental risks, and reduce construction and operational costs (Simion et al., 2023; Nazari and Musilek, 2023; El Zein and Gebresenbet, 2024).

Although oil and gas companies and other industry stakeholders involved in marine activities are adopting digital technology, their monitoring data are usually subject to confidentiality policies, which does not allow the publication of these data and their exploitation in scientific research. However, this limitation can be overcome through close and effective collaboration between industry companies and the scientific research community. This will greatly facilitate the advance of research and the improvement of scientific knowledge. It will also lead to the development of holistic digitization solutions for the management of marine infrastructure and environment, with a substantial impact on the optimization of industrial efficiency and safety.

The fundamental objective of the present study is mainly oriented towards this direction and forms part of the wider scope of the East Med Energy Research for Growth and Education Centre of Excellence (EMERGE CoE), established within Cyprus University of Technology. This study aims at contributing to the development of the energy sector in Cyprus by utilizing the advantages offered by digital technology. For this purpose, innovative in-field monitoring laboratories have been established in critical areas of the country by the EMERGE research group in cooperation with key industry stakeholders. The objective is to continuously collect valuable data related to structural and environmental parameters. This facilitates scientific research towards the development of holistic digitization solutions for the efficient and proactive management of coastal and offshore infrastructure and environment.

This paper aims to illustrate this process, identify main challenges and how they are being addressed, and define short-term plans for further developments. The objective is to exhibit and highlight the importance of employing innovative solutions that utilize state-of-the-art digitization technologies for the efficient management of marine infrastructure and environment. It also highlights the importance of effective collaboration between the scientific community and industry in the development of such solutions, describes how these solutions can be implemented in practice, and assesses their significance for the growth of the energy sector, wider socio-economic development, and environmental safety.

2. STUDY AREA AND RESEARCH INFRASTRUCTURE

The energy industry is currently one of the biggest sectors worldwide in terms of monetary value, employing hundreds of thousands of workers and generating hundreds of billions of dollars globally each year. This is greatly enhanced by the global push towards an energy transition from conventional energy production methods to the use of renewable energy sources and clean energy fuels for sustainability and environmental impact reduction purposes (Elvidge et al., 2018; Safari et al., 2019; Gielen et al., 2019). The growing need to use cleaner fuels and renewable energy sources is expected to continue to intensify, driving operators further towards the production of natural gas, the installation of wind and solar farms, and the utilization of other alternative energy sources (geothermal and hydropower).

In Cyprus, and globally, the energy industry is currently becoming one of the biggest opportunities for investment, thus making it one of the main pillars of economic prosperity and stability for the country. This is largely due to the recent discoveries of significant natural gas reserves both in the country's Exclusive Economic Zone (i.e. Aphrodite, Kronos and Calypso) and its neighbouring areas (i.e. Leviathan in Israel and Zohr in Egypt). In addition, the geographical location of Cyprus in the Eastern Mediterranean makes it an important energy interconnection hub for the region. This is further strengthened by the establishment of terminals by major oil and gas companies, such as the oil storage terminal of the international oil company VTTI. The country has also launched a plan to build the necessary liquefied natural gas (LNG) infrastructure. This will enable natural gas to be used for power generation, replacing the more environmentally harmful mazut fuel oil, with the aim of reducing carbon emissions and achieving the clean energy targets set by the European Union.

Most of the existing and planned oil and gas (O&G) infrastructure in Cyprus is established at the Vasiliko Energy Centre (VEC), covering a substantial coastal and offshore area located in the middle of the coastline between the cities of Limassol and Larnaca. A large amount of energy resources and processes are concentrated in this area, and for this reason it is considered an area of vital importance for the country, but at the same time constitutes a high-risk environment. For these reasons, the VEC offers a unique testbed for exploiting the advantages of digitization towards advancing efficiency, growth, and sustainability of the energy sector. At the same time, it enables the mitigation of hazards and risks inherent in such a highly concentrated industrial environment, thereby securing human and environmental safety.

The establishment of in-field monitoring systems in cooperation with industry stakeholders that would contribute significantly to the safe and efficient development of marine infrastructure and operational processes has been a key strategic objective of the EMERGE CoE (Votsis et al., 2018; Onoufriou et al., 2023). Such cooperation is essential for overcoming traditional barriers related to restricted access, short-term measurement campaigns, and fragmented datasets, which often limit the applicability of academic research in real operational settings. For the reasons outlined above, particular attention has first been given to the development of an in-field laboratory at the Vasiliko Energy Centre (VEC). More recently, another in-field laboratory was established in the Ayia Napa Marina (ANM), that is a new infrastructure project completed in recent years. Due to the significant interventions in the coastal environment required for the construction of this project, as well as the massive concentration of new marine infrastructure, operations, and processes in a relatively limited area, this particular field also offers an ideal testbed for exploiting innovative digitization solutions. Such solutions can streamline marina operations, ensuring both efficiency and environmental safety. They can also detect extreme and unexpected events, such as severe weather conditions or oil spills, and issue early warnings for prompt response.

Although the prospect of establishing other in-field laboratories in different regions of the country is under consideration, the research activity is currently focused on the two in-field laboratories that are already established and under continuous development at VEC and ANM, respectively. As noted previously, these in-field laboratories have been developed by the EMERGE research team in collaboration with industry stakeholders operating in these areas, who have given access to their infrastructure while continuously contributing to the installation, validation, maintenance, development and operation of these systems through their expertise and long-term experience in their fields. This long-term collaboration has enabled the deployment of permanent monitoring systems and the acquisition of continuous datasets under real operational conditions.

Real-time monitoring network systems have been installed in each of these areas, which continuously provide structural response data of critical marine infrastructure as well as information about environmental conditions and effects. While these systems allow real-time monitoring, they also enable data recording. The monitored information from the two sites is stored in a central database system. This data is utilized for research and educational purposes, supporting studies across methodological development and real-world application. As a result, research outcomes are of both scientific and practical significance. In this respect, the in-field monitoring networks aim to advance the knowledge in the digitalization of marine infrastructures, while also providing valuable information to the interested stakeholders about the condition and the efficiency of their assets and operations and the environment.

The development of the in-field monitoring networks in close collaboration with industry stakeholders represents a basic pillar of the centre's research activity and broader mission. By integrating monitoring systems directly within operational infrastructure, the study bridges the gap between academic research and practical implementation, demonstrating how data-driven approaches can be applied under real-world constraints. The latter is based on the concept of developing advanced knowledge and understanding of the conditions imposed by the concentration of critical infrastructure facilities in a marine environment. This is achieved within a wider framework in which environmental conditions and impacts are explicitly taken into account through an integrated, systematic, and holistic approach that relies on advanced digitization technologies. The aim is to enhance safety, increase efficiency, secure environmental protection, and ensure long-term viability of such critical infrastructure facilities.

3. MONITORING SYSTEMS

The areas for the installation and operation of the in-field laboratories have been carefully selected to meet multiple conditions and favor the achievement of multiple objectives, such as:

- Possibility of monitoring several targeted structural and environmental parameters.
- Availability of suitable and accessible locations for installation and maintenance of data monitoring and receiving devices.
- Possibility of easy and safe connection between monitoring and receiving devices.
- Ability to easily and securely transmit and store monitoring data.
- Existing interest of stakeholders in cooperation and active contribution.
- Strong prospect of substantial benefit for directly involved and other interested stakeholders from the outcomes of the project.
- Strong prospect of utilizing the monitoring data for the realization of essential research objectives.
- Strong prospect of substantial contribution to the development of the energy sector in Cyprus.

The Vasiliko Energy Centre (VEC) and Ayia Napa Marina (ANM) meet the above requirements. They also represent highly concentrated industrial and commercial/urban environments of national significance, where interactions between major and critical infrastructure facilities, environmental impacts, and marine operations and processes are of great importance. For these reasons, in close collaboration with industry stakeholders activated in each of these sites, the EMERGE research group designed and developed in-field laboratories comprising properly configured monitoring networks that enable real-time recording, transmission, and storage of structural and environmental data. The two monitoring systems are described next, explaining the purposes of each system, analyzing their constitutive components, the methods of data transfer and storage, as well as the importance of the data collected by each system and the prospects for their effective exploitation.

3.1. VTTV in-field laboratory

As noted in Section 2, the rapid growth of the O&G industry in Cyprus is reflected to a significant extent in the corresponding intensive development of the VEC. This development includes the establishment of a substantial number of energy infrastructure facilities, as shown in Figure 1, some of which have already been established and are in full operation, while others are included in the plans for further development. The industrial activity of large energy companies in the area, such as the VTT Vasiliko Ltd (VTTV) and the Energy Authority of Cyprus (EAC), also plays an important role in the rapid development of the VEC.

The concept of establishing an in-field laboratory in the VEC has been driven by the need for advancing holistic management solutions through digitization of infrastructure, operations, and processes involved in such a highly concentrated and rapidly developed industrial environment. Such management solutions may concern various activities that take place in this environment and are intended to offer significant benefits to the VEC stakeholders, the academic community, and the energy sector in general. Therefore, the digitization solutions provided through the in-field laboratory established in the VEC aim at satisfying the following needs:

- Optimization of the design, operation, and management of structural facilities and processes.
- Minimization of inherent risks through proactive and effective management solutions.
- Development of knowledge at an academic level with the aim of training new engineers in the field.
- Strengthening the links between academia and industry, in order to address real and timely problems that arise in practice through innovative research.

Within the framework of the above objectives, various research projects are currently underway and/or planned in collaboration with potential stakeholders. These projects include monitoring and assessment of the structural performance of major onshore and offshore infrastructure facilities, wave modelling for the VEC area, air quality and seawater quality assessment, development and implementation of pipeline technologies for design and smart predictive maintenance, and the development and implementation of smart port and coastal operations based on real-time monitoring data.

The in-field laboratory at the VEC is currently located at the premises of VTTV, consisting of a high-quality monitoring system using state-of-the-art sensing technologies. The monitoring system is located approximately 1.2 km

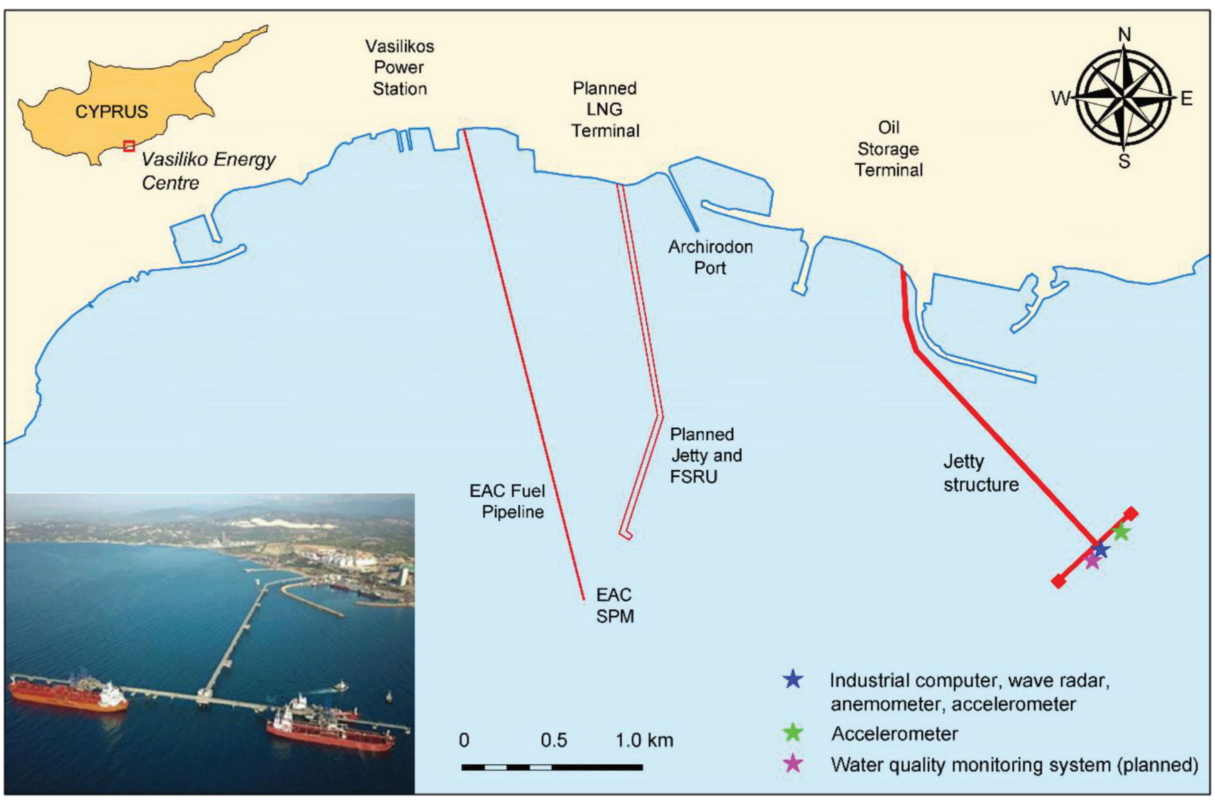


FIGURE 1
Vasiliko Energy Centre location map and layout of the monitoring system with inset aerial view.

offshore, as shown in Figure 1, and it is installed on a bottom-fixed marine jetty (Koronides et al., 2024a; Koronides et al., 2024b). This significant infrastructure, constructed during the past decade, is used for vessel berthing and the loading and unloading of petroleum products. The monitoring system has been designed for different monitoring purposes – such as structural integrity, environmental effects, operational and process system performances, etc. – and it is supported by signal processing methods and advanced analysis tools.

The sensor network includes two triaxial accelerometers (Figure 2a), located at the T-junction of the jetty and on the north-east access trestle, respectively (see Figure 1), recording X-, Y-, and Z-axis accelerations at 2 Hz with an accuracy sensitivity of ±0.4 dB over the measurement bandwidth. An anemometer (Figure 2b) installed 14 m above sea level on the T-junction measures wind speed and direction at 2 Hz. A wave radar (Figure 2c) positioned 10 m above sea level on the T-junction samples wave data at 1-minute intervals (0.0167 Hz), with an accuracy of ±0.6 mm and a measuring range of 3-65 m from the surface. All sensors communicate directly through cable connections with an industrial computer that is also installed on the same structure (Figure 2d). The industrial computer collects and temporarily stores the data, applying real-time signal processing for quality control, filtering, and visualization. The

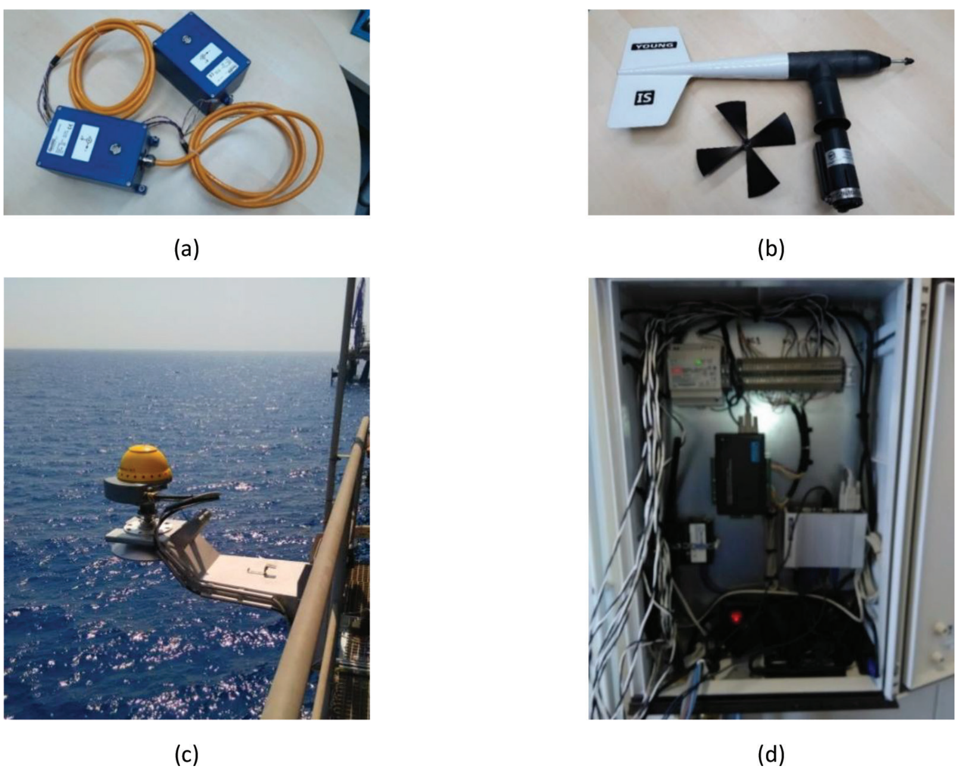


FIGURE 2
Monitoring system components of the VTTV in-field laboratory. (a) Accelerometers; (b) Anemometer; (c) Wave radar; (d) Industrial computer.

processed data are automatically transmitted to the central EMERGE database for further analysis.

Monitoring data is transferred directly to the industrial computer; thus, it can be monitored, stored, and transmitted in real time. While the data is temporarily stored on the industrial computer, it is sent in a short time interval to the internet-based data storage via an automated process. Finally, all the data is transferred and stored in the EMERGE's database; thus, it becomes available to authorized users, such as the VEC stakeholders and the EMERGE research group, for near real-time processing.

The layout and number of monitoring devices installed at the VTTV in-field laboratory have been selected to reflect the monitoring objectives and operational characteristics of the Vasiliko Energy Centre. Sensors are positioned at structurally and operationally critical locations of the jetty, where structural response and environmental loading are most representative of the overall system behaviour. This targeted configuration enables continuous and reliable monitoring of key parameters relevant to infrastructure integrity and offshore operations, while maintaining feasibility in terms of installation, maintenance, and long-term operation.

The monitoring system described above has been designed with a modular architecture, allowing the straightforward integration of additional instrumentation for monitoring further parameters that support long-term objectives. Short-term plans include the installation of a multi-parameter water quality monitoring device, which will record seawater parameters such as temperature, conductivity, salinity, resistivity, pH, oxidation-reduction potential, rugged dissolved oxygen, total dissolved solids, and turbidity. A similar instrument is already installed in the second in-field laboratory at the Ayia Napa Marina, as described in Section 3.2. Such data will be particularly useful in examining and evaluating potential impacts of energy infrastructure and operations on the marine environment.

3.2. ANM in-field laboratory

Compared to the Vasiliko Energy Centre, the Ayia Napa Marina (ANM) offers different data monitoring perspectives in a marine environment. While the former represents a heavily congested industrial environment, the latter is a commercial/residential area that has undergone substantial development over the past few years. The significant interventions in the area during the construction phase of the project, the presence and operation of new facilities, as well as the intensive use of the area due to the presence of these facilities – i.e. berthing and maintenance facilities for boats and yachts, private properties, high-rise buildings, and public areas – may have substantial influence on the marine environment.

This was the motivation that led to the design and development of an in-field laboratory in close collaboration with M.M. Makronisos Marine Ltd that manages the Ayia Napa Marina project. This new development is aligned with the principles applied to the VTTV in-field laboratory described in Section 3.1. The main objectives fall within the context of digitization, aiming at data-driven decision-making, ensuring the safety and efficient management of critical coastal infrastructure, optimizing marine operations, and protecting the marine environment.

The area of the Ayia Napa Marina and the location of the monitoring system components are shown in Figure 3. The current configuration of the monitoring system includes (Figure 4a):

- An industrial computer located near the monitoring devices to facilitate direct transfer of monitoring data via cable connections.
- A triaxial accelerometer installed on top of a concrete wall at the breakwater, recording accelerations at 2 Hz with ±0.4 dB sensitivity.
- An all-in-one weather station measuring temperature, humidity, barometric pressure, wind speed, and wind direction.
- A multi-parameter seawater quality monitoring device, equipped with various sensors able to monitor temperature, conductivity, salinity, resistivity, pH, oxidation reduction potential (ORP), rugged dissolved oxygen (RDO), total dissolved solids (TDS), and turbidity. It is placed on the seabed at a distance of about 25 meters south of the foot of the breakwater (Figures 3 and 5), in the area near the industrial computer (Figure 4b).
- A wave reader that enables monitoring of various environmental parameters, such as wave spectra, wind speed, sea surface temperature and barometric pressure (Figure 6a).

All of the above monitoring devices, with the exception of the wave reader, are directly connected with the industrial computer that is installed on the breakwater through cable connections. In this way, the recorded data is transferred directly to the industrial computer; thus, it can be recorded, stored and transmitted in real time. Similar to the VTTV network system described previously, while the data is temporarily stored on the industrial computer, it is automatically sent in a relatively short time interval to the internet-based data storage. The database in which the data is finally transferred and stored is the same as that used for the data received from the VTTV network. Therefore, a central database is used for both in-field laboratories, which can be easily accessed by authorized users.

The wave reader is the first component of the monitoring system that is not directly connected to the industrial computer via a cable connection. The reason is twofold. On the one hand, this instrument is installed in an offshore area quite remote from the industrial computer, near the left end of the breakwater, as shown in Figure 3. On the other hand, it enables real-time data transfer through a wireless cellular connection. The system comprises a small solar-powered buoy (Figure 6a) which is accessed and configured remotely via an online dashboard (Figure 6b). The monitoring data is transferred in near real-time and can be accessed online as shown in Figure 6b. This example shows the variation in significant wave height (in m) and wind speed (in m/s) over the period between 15 and 20 February 2025. Additionally, the remaining monitored parameters mentioned above can be visualised in the same way. The exact position of the instrument per time period is also displayed. Similar to the other monitoring systems, the monitoring data obtained from the wave reader is transferred and stored in the EMERGE database for further processing and utilisation in research studies and other purposes. This transfer and storage can occur automatically in near real-time through a capability offered by the instrument provider's dashboard, enabling timely in-depth data interpretation.

FIGURE 3
Ayia Napa Marina location map and layout of the monitoring system with inset aerial view.

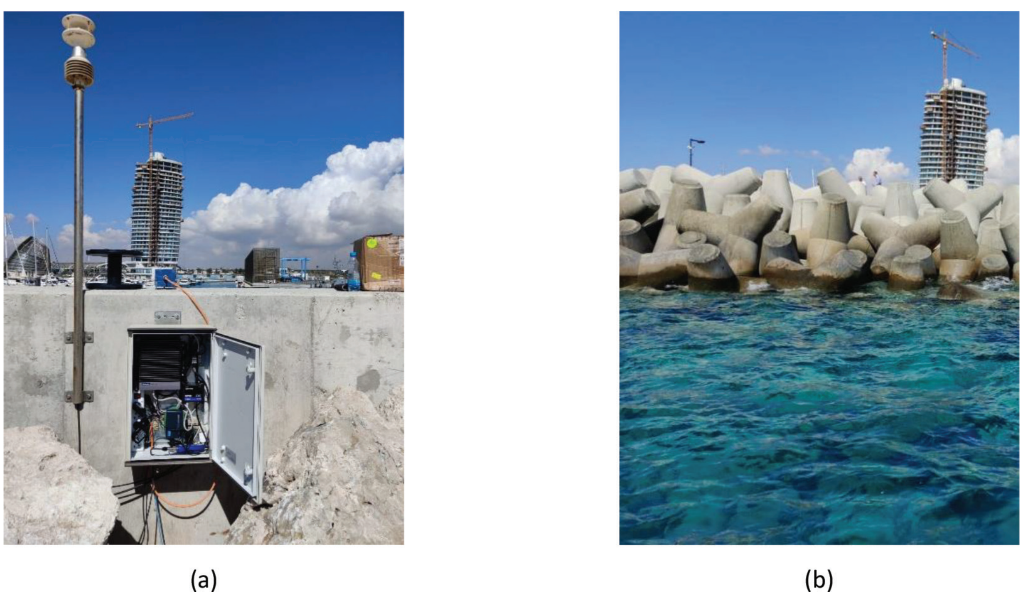


FIGURE 4
ANM in-field laboratory. (a) Industrial computer, weather station and accelerometer installed on the breakwater; (b) Offshore area in the vicinity of the industrial computer.

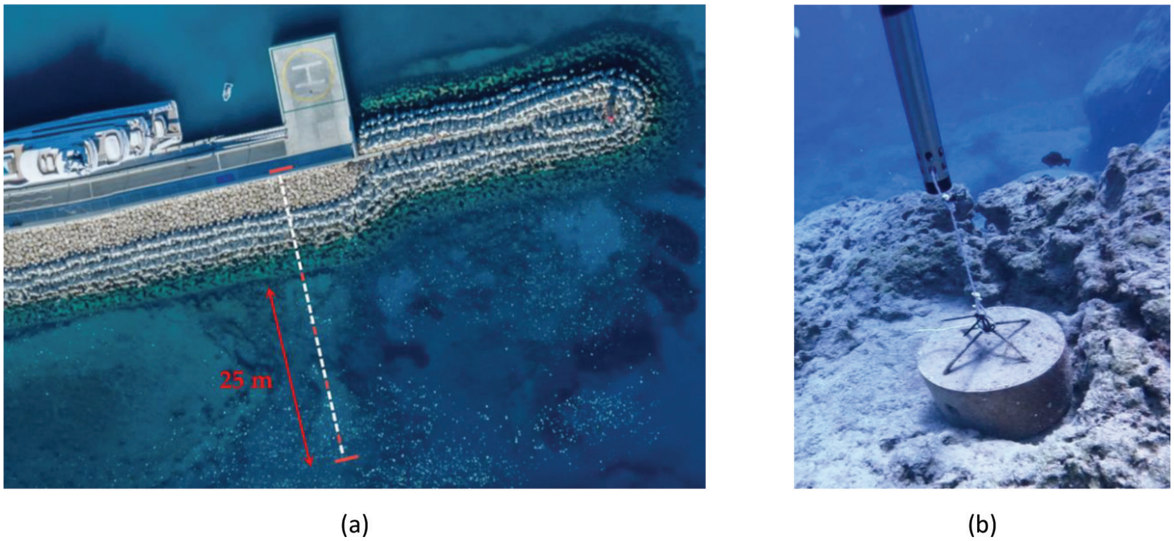


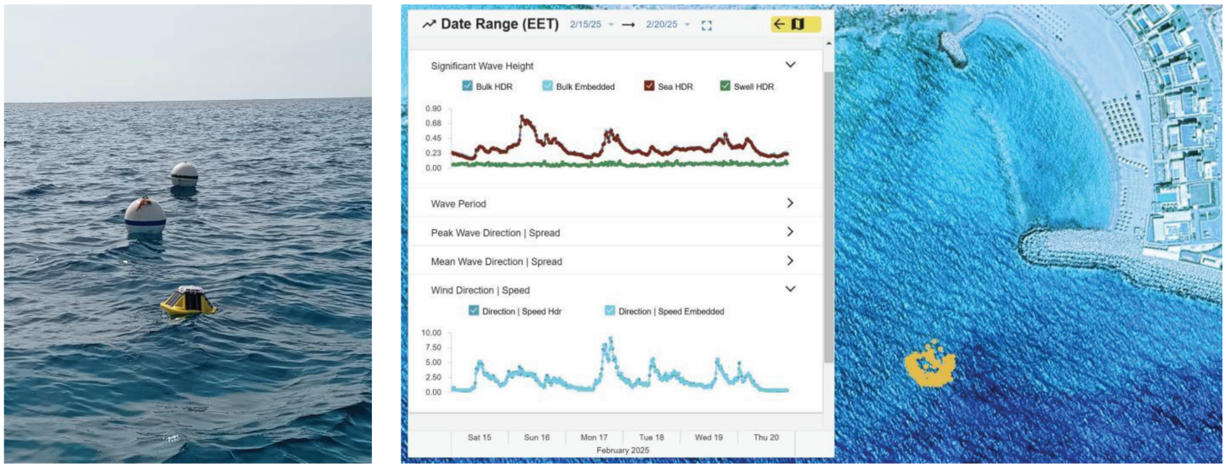
FIGURE 5
Setup of the water quality monitoring system. (a) Installation point near the industrial computer area; (b) Anchoring of the instrument to the seabed.

The mooring system of the wave reader is based on a double catenary design, comprising two surface floats as shown in Figure 6a. The instrument and the two floats are connected in series via two 10-meter-long catenary loops. A vertical section connects the second float to an anchor chain that secures the system to an anchor weight at a depth of approximately 6.5 m on the seabed. The mooring system has been carefully designed, taking into account the characteristics of the area and the specifications provided by the manufacturer, to ensure controlled movement of the instrument within a specific area and to minimize constraints in motion, thereby enabling the collection of accurate wave and wind motion data.

The configuration of the monitoring system at Ayia Napa Marina has been designed to address the specific environmental and operational conditions of a coastal commercial and residential setting. Monitoring devices are strategically placed to capture representative environmental conditions and structural responses associated with marina operations and coastal infrastructure. The selected number and placement of sensors provide continuous and indicative monitoring of key parameters affecting environmental quality and infrastructure performance, while ensuring practicality in deployment and maintenance. As with the VTTV system, the monitoring framework is modular, enabling refinement or expansion in response to evolving monitoring needs.

3.3. Data acquisition, processing, storage and use

The two in-field laboratories established in the two different strategic locations in Cyprus – i.e. the Vasiliko Energy Centre and the Ayia Napa Marina, as described in Sections 3.1 and 3.2, respectively – constitute an extensive monitoring system that collects a substantial volume



(a) (b)

FIGURE 6
Setup of the wave reader system. (a) Sea surface configuration of the system; (b) Real-time data visualization.

of real-time structural and environmental data. Due to the large amount of information, the different sources, and the many different types of parameters, efficient and secure management and storage of the monitoring data is of utmost importance. For this reason, special attention has been given to the development of an efficient data transfer, processing and storage process, with the final destination being a central database.

The configuration of the monitoring systems at the two sites reflects the different characteristics, operational conditions, and monitoring objectives of each location. The Vasiliko Energy Centre represents a heavily industrialized offshore-coastal environment with critical energy infrastructure, where monitoring priorities focus on structural integrity, wave loading, and atmospheric conditions that may affect offshore operations. In contrast, the Ayia Napa Marina is a coastal commercial and residential environment, where monitoring is oriented towards environmental quality, marina operations, and the interaction between environmental conditions and coastal infrastructure. Consequently, while some monitoring components are common to both sites (e.g. accelerometers and meteorological measurements), differences in sensor types, measured parameters, and sampling rates are intentionally adopted to address site-specific requirements and intended applications. A summary of the monitoring components and their respective parameters and sampling rates for each site is provided in Table 1.

As described in Figure 7, the raw data monitored by the sensors are temporarily stored on local industrial computers available on each site. The data is then transferred via internet-based data storage to the EMERGE servers located at the premises of the Cyprus University of Technology. Finally, the data is inserted in the EMERGE central database and processed using Python-based scripts for quality control, filtering, and visualization. The queries are generated by Python scripts, developed specifically for this purpose. First, the script reads the raw data files and extracts the data values; an SQL statement is then generated for inserting the data values in the database. The datasets collected are subsequently used in advanced analyses, including machine learning studies as described in Section 4.

In the context of infrastructure and environmental management, the continuous acquisition and centralized processing of monitoring data enable near real-time awareness of system behaviour. By providing timely information on structural response and environmental conditions, the monitoring framework supports early identification of abnormal trends, facilitates informed decision-making, and enables proactive management actions such as targeted inspections, operational adjustments, or preventive maintenance. In this way, continuous monitoring forms the basis for active management strategies rather than reactive responses.

A key objective of the whole process is to make the data easily accessible and usable to interested users, either for data analysis and scientific research or to support the optimization of infrastructure management and operational processes by industry stakeholders in practice. One possible approach is the incorporation of higher-level applications into the database. In this way, selected data can be retrieved directly from the database, either in the form of tables or through graphical representations such as in the form of diagrams or charts. Substantial progress has already been made in this direction as explained in the next section, but this is an important element of the whole process that requires continuous improvement and upgrading.

4. PROJECTS AND APPLICATIONS

As described in Section 2, the strategic mission of the EMERGE CoE is to contribute to the prosperous development of marine infrastructure and the environment through advanced

TABLE 1
Monitoring system components and parameters

Sites	*Monitoring devices*	*Number of parameters*	*Main parameters*	*Sampling rates*
VTTV in-field laboratory	Anemometer	2	Wind Direction, Wind Speed	2 per second
	Wave radar	16	Significant Wave Height, Mean Wave Period	1 per minute
	Accelerometers	3	X-axis, Y-axis, Z-axis accelerations	2 per second
	Water quality monitoring	16	Temperature, Conductivity, Salinity, Resistivity, Water Density, pH, ORP, Rugged Dissolved Oxygen, TDS, Turbidity	1 per 30 minutes
ANM in-field laboratory	Weather station	16	Wind Direction, Wind Speed, Temperature, Relative Humidity, Atmospheric Pressure	1 per second
	Accelerometer	3	X-axis, Y-axis, Z-axis accelerations	2 per second
	Water quality monitoring	16	Temperature, Conductivity, Salinity, Resistivity, Water Density, pH, ORP, Rugged Dissolved Oxygen, TDS, Turbidity	1 per 30 minutes
	Wave reader	10	Wave Height, Wave Period, Wind Speed, Sea Surface Temperature, Atmospheric Pressure	1 per 5 minutes

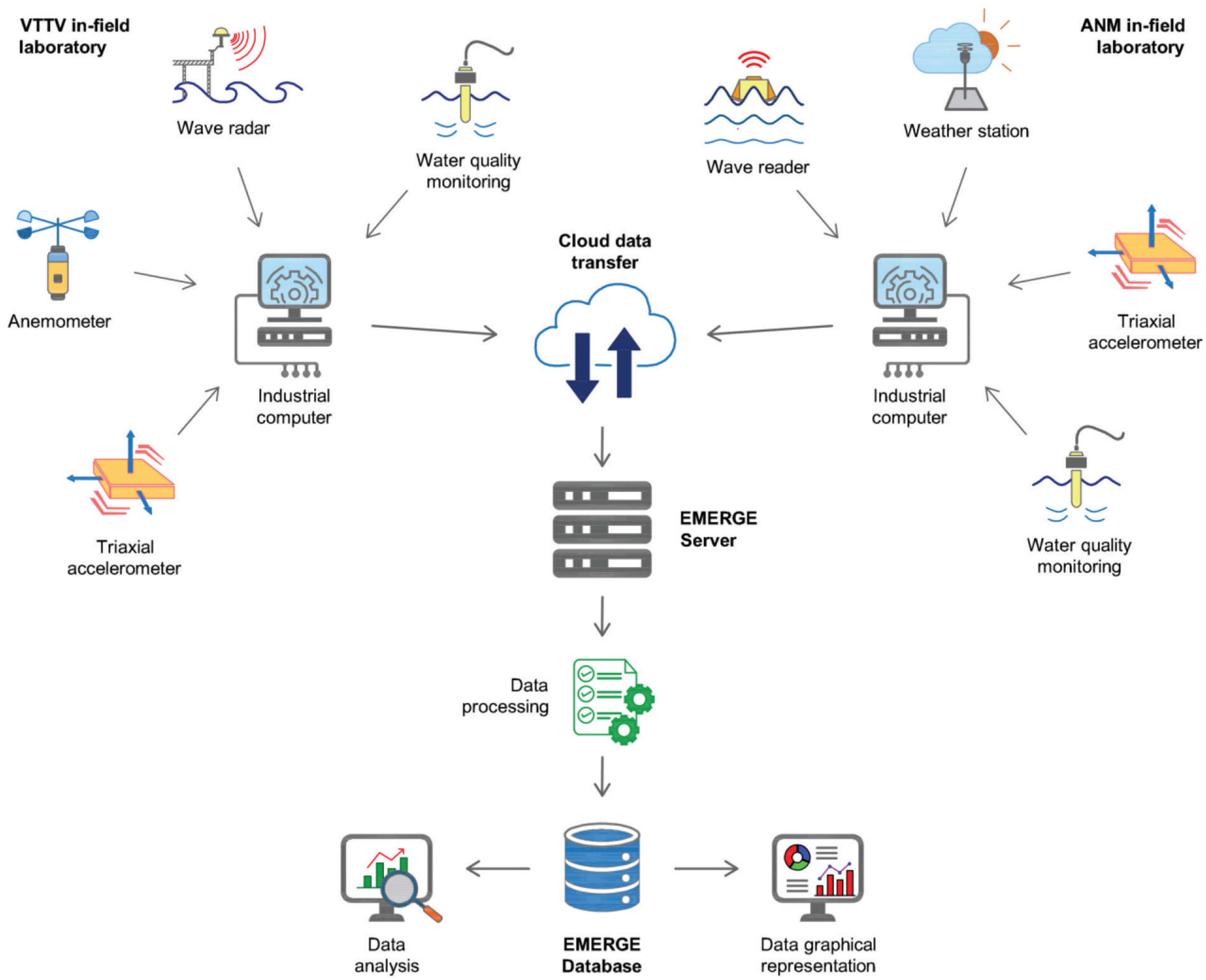


FIGURE 7
Process of data flow from sensors to database and end users.

digitization studies. These studies exploit the massive amount of data produced by the established in-field laboratories described in Section 3. This section describes some of the steps being taken in this direction, and how the data obtained from the monitoring system are being used by the EMERGE research group and by other involved stakeholders, both for research purposes and for the better management of structural assets and processes in practice. Plans include further development of the monitoring system, in the context of a wider flagship project aimed at the holistic digital transformation of the Vasiliko Energy Centre, as described in Section 5.

4.1. Samples of wind and wave data

This section presents samples of wind and wave data obtained from the VTTV in-field laboratory at the Vasiliko Energy Centre. The collection of wind and wave data presented herein corresponds to a 28-day reference period, which is the time period between September 1 and September 28, 2024. The sampling frequency is shown in Table 1.

Figure 8 provides a graphical representation of the interplay between wind speed and wind direction for the 28-day reference period. As noted previously (Table 1), the original wind data are measured at a rate of 2 samples per second. Figures 8a and 8b show the corresponding average per minute and average per hour values, respectively. The wind speed data were calculated based on arithmetic averages, while wind direction data was calculated based on circular averages. The wind rose charts of Figure 8 illustrate the durations of different wind directions as percentages of the total time period, while also showing the corresponding wind speed values for each direction and time interval.

What is particularly important is that both diagrams describe the wind characteristics in a similar way, despite the fact that they represent significantly different amounts of data. This information can be particularly useful for simplifying data processing in daily routine applications. Therefore, an important part of analyzing and utilizing the data obtained from the in-field laboratories is determining the optimal combination of data volume and accuracy, depending on the type of the data and the length of the reporting period.

Figure 9 shows the variation of the average wind speed per minute for the 28-day reference period. In the same figure, the variation of the 1-hour average values, together with the 1-day (24-hour) moving average, displaced

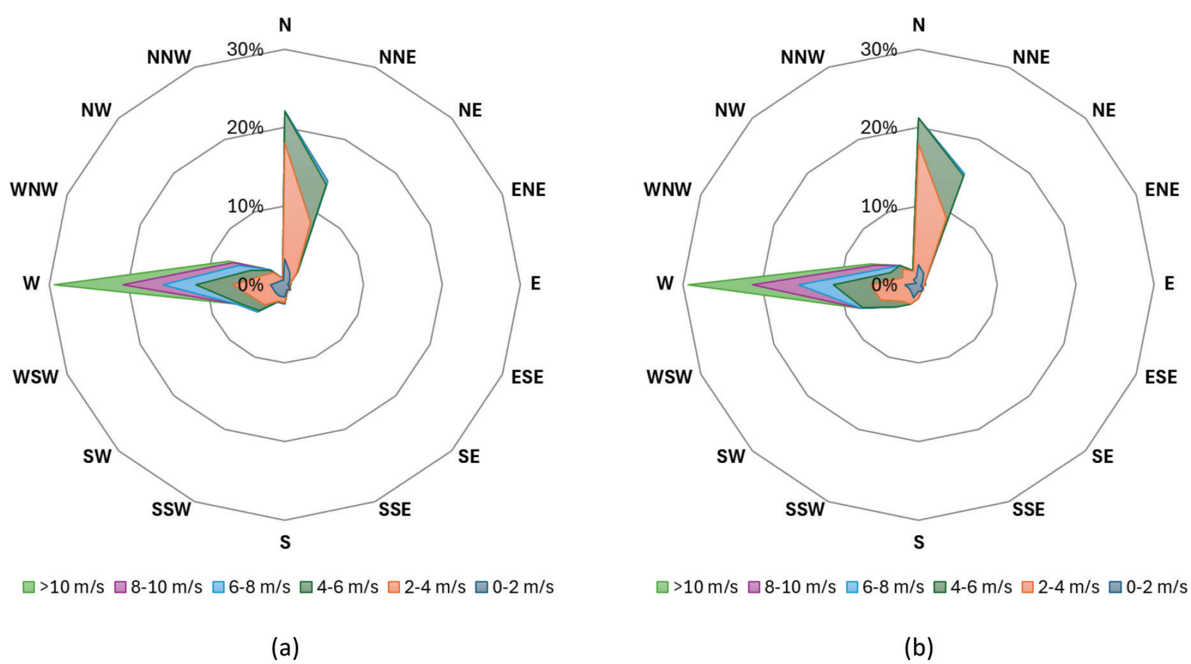


FIGURE 8
Wind rose charts for the 28-day period. (a) Average per minute data (40320 values); (b) Average per hour data (672 values).

backwards by 12 hours, are presented. Together with the charts of Figure 8, the time history plots of Figure 9 facilitate understanding the wind characteristics over the reference period. As in Figure 8, the hourly average values provide a representative approximation of the variation of wind speed with time. Furthermore, the trend of wind speed over time is adequately described by the 24-hour moving average. Such simplifications can significantly facilitate applications that do not require a particularly high degree of accuracy in data distributions, such as the daily monitoring of environmental conditions.

Figure 10 shows the variation of the significant wave height and mean wave period with time for the 28-day reference period. As noted previously (Table 1), wave data at the VTTV in-field laboratory are monitored at a rate of 1 sample per minute, so the curves of Figure 10 are based on the original monitoring data. For both wave parameters, the same figure depicts the variation of the 1-hour average values, together with the 1-day (24-hour) moving averages displaced backwards by 12 hours.

As shown in Figure 10a, the variation in significant wave height exhibits an almost periodic trend, characterized by relatively smooth transitions between minimum and maximum values of approximately 0.5 m and 1.5 m, respectively, with few exceptions of larger deviations. By correlating the data in Figure 9 with those in Figure 10, it is observed that the values of significant wave height and mean wave period start to increase immediately after a short period of high wind speeds. Although wind data and wave data are recorded by different instruments with different sampling rates, comparing and correlating these data is essential to understanding the potential interactions between these parameters. This preliminary observation demonstrates the value of the current monitoring system as an integrated platform for multi-parameter analysis, enabling the identification of coupled environmental effects and supporting more robust interpretation, validation, and forecasting of coastal dynamics.

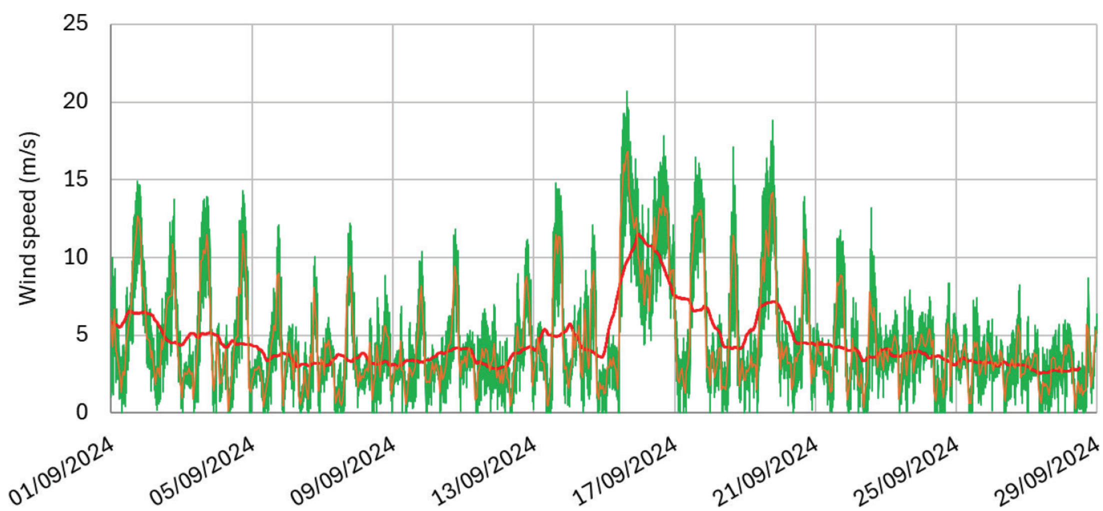


FIGURE 9
Time variation of wind speed, averaged per minute, hour, and 24-hour moving average.

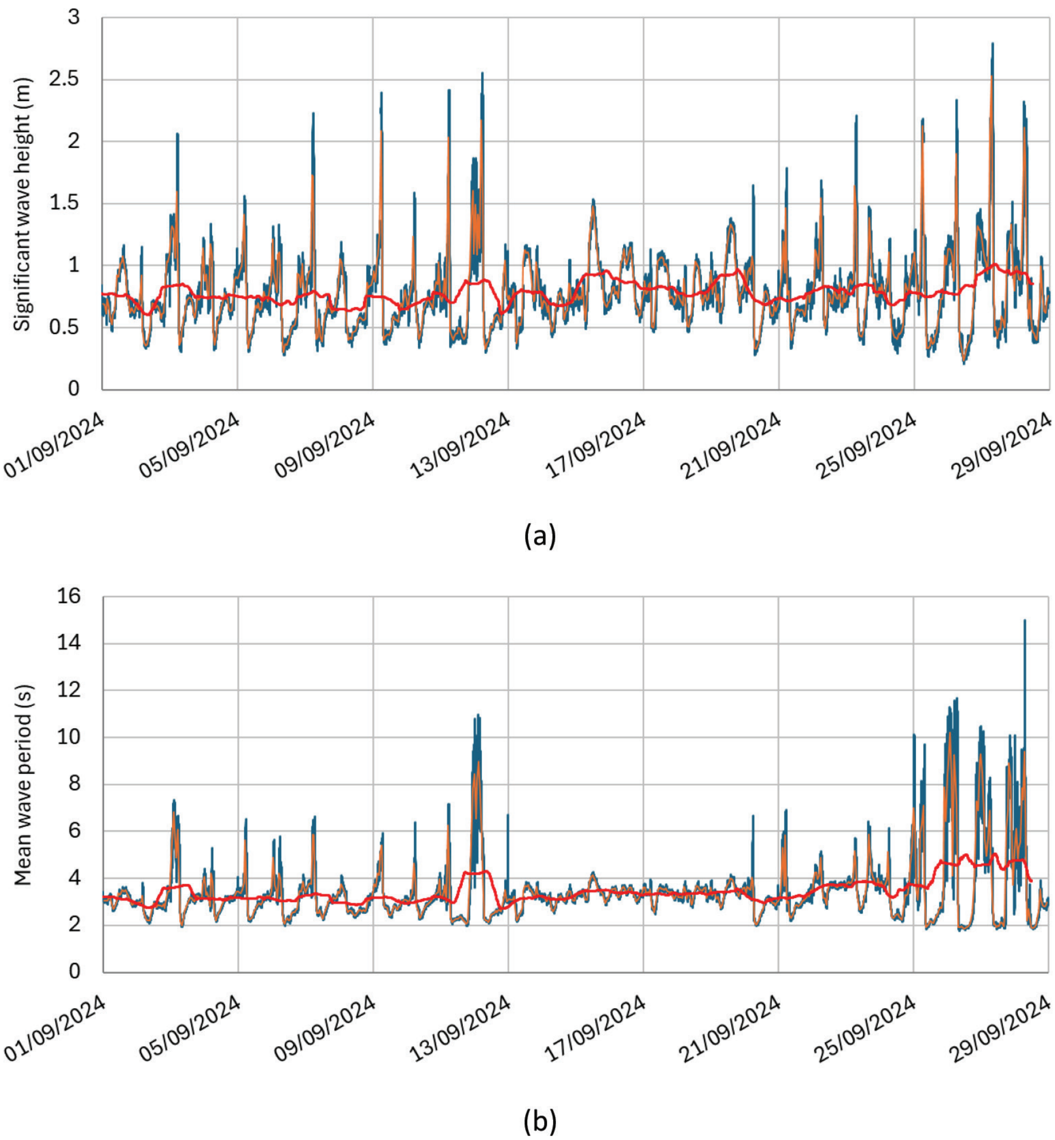


FIGURE 10
Time variation of wave data, averaged per minute, hour, and 24-hour moving average. (a) Significant wave height; (b) Mean wave period.

4.2. Reduced database and automated daily reports

As noted in Section 3.3, one of the main purposes of the in-field laboratories established at the Vasiliko Energy Centre (VEC) and the Ayia Napa Marina (ANM) is to make monitored data readily available to interested users, namely the EMERGE research group and the industry stakeholders operating in these areas. The collected datasets are intended to support research activities and assist stakeholders in optimizing their operational and maintenance activities. For this purpose, particular importance is given to streamlining the generation of automated reports of measured parameters through post-processing of the monitoring data.

According to Table 1, wave data are monitored at a rate of one sample per minute while wind data are monitored at a rate of 2 samples per second. As explained in Section 4.3, a high recording rate is not always necessary as a potential improvement in data accuracy may be disproportionate to the increased data volume. This of course depends largely on the time period being examined and the type of data. Therefore, for the purposes of daily reports describing the variations of wind and wave data during a 24-hour period, it is important to first determine the appropriate sampling rate. This parameter must simultaneously ensure data accuracy and the simplicity of the process of producing such daily reports.

Figure 11a describes wind speed and direction for September 28 based on the given recording rate of 2 samples per second (Table 1). Figure 11b describes the same parameters based on 1-minute average values. For the same data, a similar comparison of the corresponding wind speed time-history plots is shown in Figure 12. Based on both figures, it is observed that the wind characteristics during the 24-hour reference period are described with a similar degree of accuracy either by a total of 172,800 data points (corresponding to 2 samples per second) or by a total of only 1440 data points (corresponding to 1-minute average values). The main difference between the two representations is essentially the minimization of high-frequency data noise when considering 1-minute averages.

Based on these findings, wind and wave data can be collected together using the common time step of 1 minute. For this purpose, appropriate processing of the original data transferred from the in-field laboratories to the EMERGE servers is needed, so that a dataset with the requested characteristics can be stored in the database as presented in Table 2. For the intended purpose of this dataset, this process should be performed in near real time and should therefore be automated, easy, and simple. Such a simplified dataset offers the following advantages:

- The original database is not affected, since the reduced dataset is an additional component of the database system.
- The volume of data of the reduced dataset is significantly smaller compared to the original database.
- The transfer and storage of data to the reduced dataset requires relatively little time, so this can be done in near real time.
- The processes of data processing, data transfer, and storage are automated through appropriate algorithms that are specifically configured and designed for this purpose.
- Due to the simplicity of the dataset, automating the process requires much less time than automating the transfer of the original data to the database.
- Since the dataset is updated in real-time, the verification of the availability and validity of data is considerably facilitated. For example, missing data are easily detectable, as in the case of some wave data missing from the dataset given in Table 2.
- Since wind and wave data are stored with a common timestamp, direct correlation between corresponding parameters becomes possible.

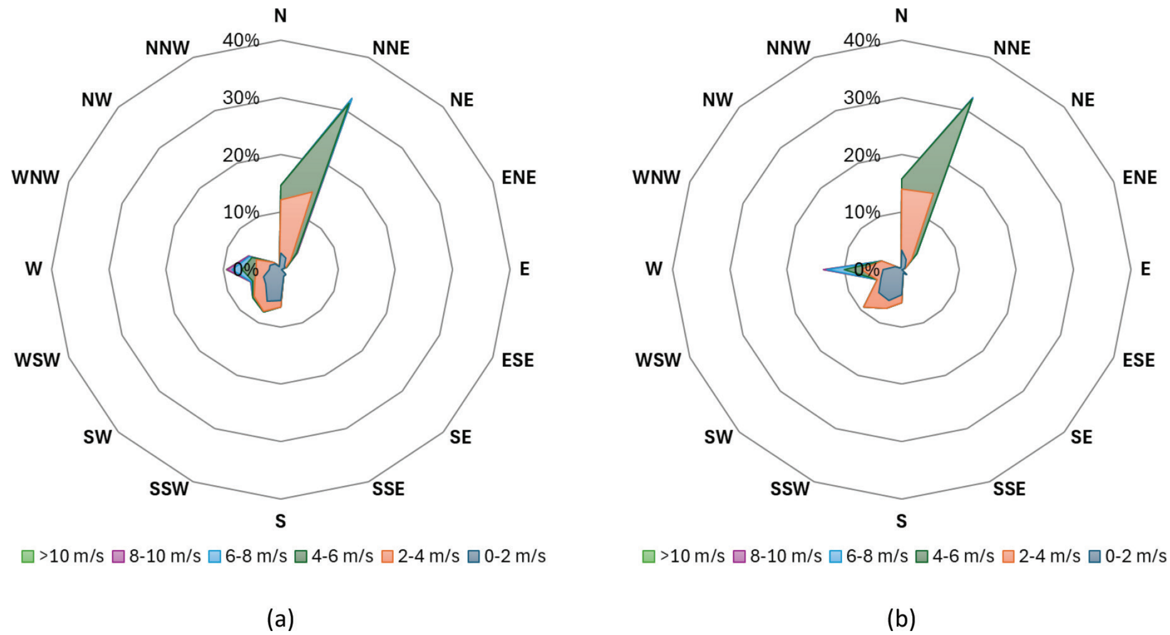


FIGURE 11
Wind rose charts for September 28, 2024. (a) All data (2 recordings per second, i.e. 172800 values); (b) Average per minute data (i.e. 1440 values).

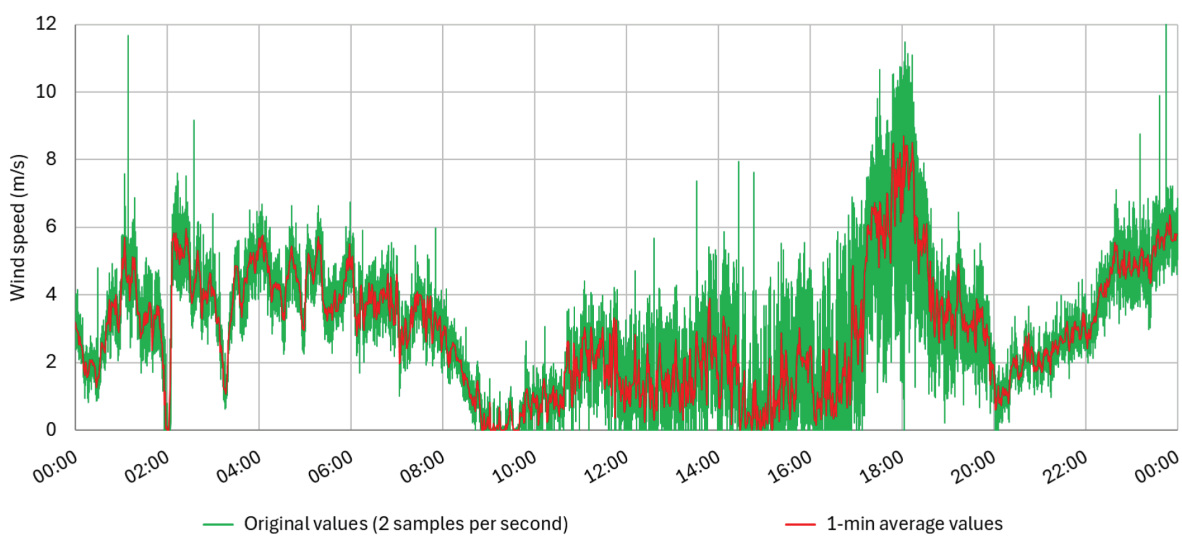


FIGURE 12
Wind speed time-history plots for September 28, 2024.

- The data can be used directly for research purposes without requiring further processing.

With further development of the automated process of transferring a reduced volume of selected data to a separate space of the database

TABLE 2
Sample of the structure of the reduced database

time_stamp	*wind_dir1*	*wind_speed2*	*H4rms_m3*	*Tz_s4*
⋮	⋮	⋮	⋮	⋮
28/09/2024 16:10:00	267.17	0.646	0.537674	2.25848
28/09/2024 16:09:00	264.91	1.113	0.528424	2.25276
28/09/2024 16:08:00	273.67	0.151	0.522088	2.26241
28/09/2024 16:07:00	259.76	0.327	0.522547	2.27959
28/09/2024 16:06:00	242.03	0.288	0.52705	2.27577
28/09/2024 16:05:00	256.41	0.616		
28/09/2024 16:04:00	244.65	1.259		
28/09/2024 16:03:00	235.25	1.122		
28/09/2024 16:02:00	236.48	2.044	0.496526	2.21745
28/09/2024 16:01:00	233.85	2.438	0.458671	2.21174
28/09/2024 16:00:00	231.29	2.489	0.437346	2.18112
⋮	⋮	⋮	⋮	⋮

[1]Wind direction (degrees); [2]Wind speed (m/s); [3]Significant wave height (m); [4]Mean wave period (s).

in near real time, the integration of automated graphical representations is facilitated. This can serve many purposes, one of which is the option to graphically preview selected parameters for selected time periods in the form of Graphical User Interfaces (GUIs). Another perspective is the automated production of daily reports describing the structural condition of assets and the characteristics of the environment in near real-time.

An example of a daily report regarding wind and wave parameters in the VEC area, based on monitoring data from the VTTV in-field laboratory, is presented in Figure 13. This report includes:

- A polar scatterplot that describes the relationship between wind speed and wind direction.
- Time-history plots of wind speed, significant wave height (H4rms) and mean wave period (T_z).
- A scatterplot showing the possible interaction between wind speed and significant wave height.

Time periods with different characteristics can be defined using different colours as shown in Figure 13, which facilitates understanding the variation of wind and wave data during the 24-hour period. This type of graphical representation of selected data is a straightforward process, as no further processing is required, which is one of the inherent limitations when graphically representing data stored in the original database.

4.3. Data-driven wave modelling studies

Knowledge and understanding of wave parameters are key components in developing effective methods for managing marine infrastructure and the environment. Data-driven

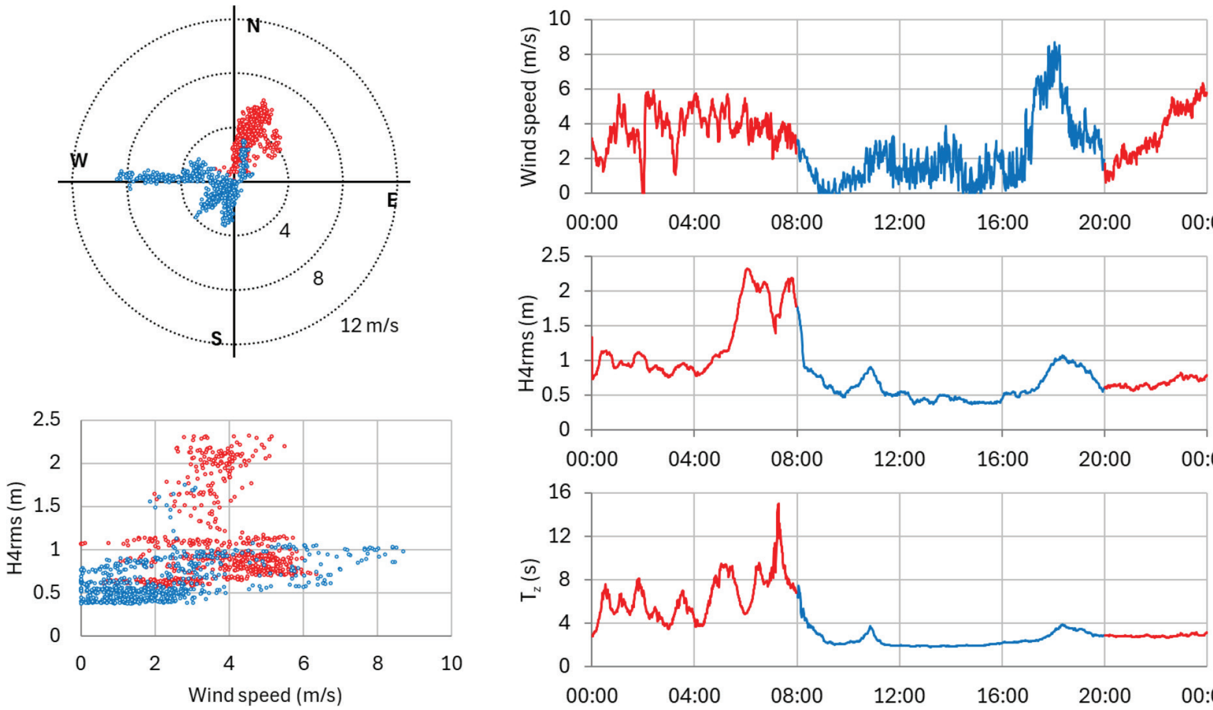


FIGURE 13
Example of a daily report (September 28, 2024) of wind and wave data indicating periods of different characteristics with different colours.

wave characterization methods utilizing real-time monitoring data integrated with machine learning applications may offer substantial advantages over the traditional complex and computationally intensive numerical approaches (Kumar et al., 2018; Shamshirband et al., 2020; Abouhalima et al., 2024). The objective of such methods is to facilitate and improve the prediction of wave characteristics by utilizing readily available structural and environmental data, without requiring sophisticated and expensive sensing equipment capable of measuring these parameters with precision (e.g. wave radars and wave buoys).

In this perspective, the EMERGE research group developed a method for real-time prediction of significant wave height (SWH) using meteorological and structural monitoring data for the training of supervised machine learning methods (Demetriou et al., 2021a). Specifically, the study used monitoring data from the VTTV in-field laboratory, including structural acceleration data and wind speed/direction data collected respectively from the accelerometers and the anemometer installed on the jetty structure shown in Figure 1. The features extracted from these data were used as training inputs in both artificial neural networks and decision tree assemblies, and they were tested on field data recorded by the wave radar installed on the same structure (Figure 1).

The study has proved that available meteorological and structural acceleration data, which are often available through the structural monitoring equipment installed on offshore and coastal infrastructure, can yield models of enhanced SWH predictive capacity. The outcomes suggested that structural data can significantly influence the performance of the prediction models, while classification algorithms can be successfully applied in the nowcasting of SWH. Based on the latter, further studies were conducted with the aim of exploiting the concept of classification predictive modelling of SWH through the development of hierarchical machine learning classification models (Demetriou et al., 2021b). This has led to the development of optimized classification models with improved performance in terms of both increased accuracy and computational efficiency in predicting SWH.

These studies have provided significant insights into the potential of real-time prediction of wave parameters through data-driven machine learning methods. Most importantly, the promising outcomes of these studies highlighted the potential for future work to be undertaken in this area. Indeed, the intense research activity in this direction shows that researchers are increasingly turning their focus to the further development and exploitation of such methods (Wei, 2021; Mahmoodi and Nowruzi, 2022; Huang et al., 2023; Hasan et al., 2024). The impact of these studies on the advancement of knowledge and the development of effective methods for managing the marine environment is expected to significantly benefit energy stakeholders and other operators involved in marine activities.

4.4. Seawater quality studies

As described in Section 3.2, the Ayia Napa Marina has undergone substantial development over the past few years, with a complete reformation of the area and the construction of new modern infrastructure. In such major interventions, there is a significant risk of environmental impacts, both during the construction phase and in the long-term during the operation phase of the project. For this reason, one of the key parameters examined through the monitoring system established in the area is the quality of the water. As noted in Section 3, a suitable system has been installed on the seabed in close proximity to the marina breakwater for continuous monitoring of various seawater characteristics (Table 1). The monitoring data is used for real-time water quality assessment as well as for research purposes.

In a recent study (Koronides et al., 2024c), time and frequency domain analyses together with filtering techniques were employed for post-processing water quality data, with the aim of extracting useful information about the state of the seawater quality and potential temporal or cyclic variations in the various water quality parameters. The study showed that the construction and operation of the new facilities in the area did not affect marine water quality, since data processing yielded water quality parameters that align with expected values associated with open sea conditions in the coastal environment of the wider area. In addition, the study identified a pronounced daily cyclic response in many water quality parameters and observed notable correlations among these parameters (Koronides et al., 2024c).

Although this particular study is based on a limited sample of measurements within a 3-month period, the results provide important information at least for the water quality status in the period immediately after the completion of the construction works of this major project in the area. Through continuous monitoring, post-processing of data, and appropriate assessment of possible variations in the values of these seawater parameters over time, more useful and reliable information will be continuously obtained. Additionally, real-time processing of the monitored data will facilitate early detection of adverse events, such as oil spills, and enable prompt response to implement mitigation measures.

5. IMPORTANT ASPECTS OF THE STUDY

5.1. On-going and future developments

As shown in Figure 1, several major energy assets are concentrated in the VEC area. Two oil storage terminals (operated by VTTV and Petrolina, respectively) are already installed in the onshore area, while the largest power station of the country operated by the Electricity Authority of Cyprus (EAC) is located in the same area. For the station's operational needs, important offshore infrastructure is also installed, such as a subsea fuel pipeline and a single point mooring (SPM) system. The large concentration of energy infrastructure is expected to further increase in the near future. A liquefied natural gas (LNG) terminal, along with another jetty serving a floating storage regasification unit (FSRU), as well as a subsea gas pipeline system, are currently under study and development.

The more the VEC area is congested by the concentration of additional assets and operations, the more imperative it becomes to establish innovative and effective methods of managing operations, ensuring infrastructure integrity, and minimizing inherent risks. Taking advantage of the possibilities offered by digital technology and following the same path as the installation of the main part of the VTTV in-field laboratory, the next step is to expand the monitoring network to include most of the existing or future operations and assets. This will lead to the development of a global monitoring system for the entire VEC area that will allow the monitoring of multiple structural and environmental parameters in real time. This will contribute to improved management of potential emergency situations, while also creating a database for research purposes.

The ultimate objective of this flagship project is to provide a holistic solution for improving structural, environmental, and operational conditions in the VEC area. This holistic solution aims to satisfy the following needs:

- Secure the structural robustness and the integrity of critical infrastructure, thus ensuring their unobstructed operation.
- Enhance the resilience of ageing energy infrastructure through continuous structural monitoring and timely intervention.
- Contribute to the protection of the environment and the safety of operators and the wider community.
- Promote proactive management of operations and assets.
- Optimize future infrastructure design and operation.
- Develop effective links and synergies among stakeholders, especially between academia and industry.

In this context, continuous monitoring plays a central role in supporting proactive and active management of marine infrastructure and operations. The real-time availability of structural and environmental data enables operators and stakeholders to maintain continuous situational awareness of system behaviour. Rather than relying on periodic inspections or reactive responses, management actions can be informed by observed trends and evolving conditions, allowing early identification of potential issues and timely intervention. In practice, this approach supports active management strategies such as targeted inspections following abnormal responses, adjustment of operational parameters under adverse environmental conditions, and prioritization of maintenance activities based on observed performance. By integrating monitoring outputs into decision-making processes, the proposed framework provides a foundation for condition-based management and improved resilience of marine infrastructure.

The availability of structural health monitoring and environmental monitoring data also creates opportunities for future interdisciplinary applications. In particular, the combined analysis of environmental conditions (e.g. wave, wind, and water quality parameters) with structural response data can support the development of integrated assessment frameworks, enabling improved understanding of environment-structure interactions. Such approaches may facilitate the formulation of advanced management strategies, including condition-based maintenance, adaptive operational planning, and data-driven risk mitigation, contributing to more resilient and sustainable management of marine infrastructure.

This holistic digitization solution will be based on real-time monitoring data, supported by artificial intelligence methods (Demetriou et al., 2021a; Demetriou et al., 2021b), signal processing (Koronides et al., 2024c), and advanced analysis tools (Koronides et al., 2024a; Koronides et al., 2024b).

5.2. Demands and challenges

The process of holistic digital transformation of marine infrastructure and environment is demanding and requires appropriate expertise, planning, management, continuous development, and substantial investment. It is found that this process involves several challenges, such as the following:

- A highly concentrated marine environment may generate many different types of data. For optimal system efficiency, the monitoring process should be limited to parameters of essential importance. Therefore, proper system design is particularly important.
- Also important is the selection of the most appropriate monitoring equipment, which must satisfy the needs of the project but also meet the requirements and particularities of the installation field.
- The type of monitoring instruments and their installation points must be carefully chosen to facilitate periodic inspection and maintenance, while the feasibility of data transfer – either through wired or wireless connections – should also be carefully taken into account.
- As the monitoring system can be continuously expanded by adding new monitoring devices or replacing some devices with other equipment of different capabilities, the data transfer, processing and storage methods must be able to readily adapt to these changes.
- Particularly important is the collaboration between individuals from different specializations, who constitute a multidisciplinary team, while equally important is

the effective collaboration between different stakeholders and especially between research community and the industry.

Although these challenges make the whole process particularly demanding, it has been shown that the more carefully and efficiently they are addressed, the more significant the expected benefits of the project become. To further contextualize the value of addressing these challenges, the proposed monitoring approach is compared in the following subsection with conventional monitoring practices commonly applied in marine environments.

5.3. Comparison with conventional monitoring approaches

Conventional monitoring of marine infrastructure and environmental conditions is typically based on periodic inspections, short-term measurement campaigns, or the deployment of standalone instruments operating independently. While such approaches can provide useful snapshots of system behaviour, they often suffer from limited temporal resolution, delayed data availability, and fragmented datasets, which restrict their effectiveness for proactive management and decision-making.

In contrast, the monitoring systems presented in this study are based on continuous, multi-parameter, near real-time data acquisition, enabling simultaneous observation of structural and environmental conditions. For example, acceleration and meteorological data are recorded at sampling rates up to 2 Hz, while wave and seawater quality parameters are monitored at regular multi-minute intervals. This represents a substantial improvement over conventional approaches, where measurements are often collected at lower frequencies or during discrete campaigns. From an operational perspective, the proposed systems reduce the need for frequent on-site inspections, particularly in offshore or hard-to-access environments, improving efficiency and safety.

The centralized data management architecture facilitates secure storage, rapid access, and integrated analysis of large datasets, which in turn supports efficient decision-making and long-term system evaluation. In this context, although a detailed quantitative cost-benefit analysis is beyond the scope of this study, the long-term deployment of integrated monitoring systems offers economic advantages over traditional monitoring practices by enabling early detection of structural or environmental changes, supporting condition-based maintenance, and improving environmental management strategies.

Beyond these immediate operational benefits, continuous and long-term monitoring provides the foundation required for the development of advanced data-driven analysis tools, including machine learning, statistical modelling, and digital twin frameworks. The availability of high-quality, synchronized structural and environmental datasets enables the identification of complex patterns and trends that cannot be captured through conventional monitoring. In this respect, continuous monitoring acts as a key enabler of holistic digital transformation for marine infrastructure and environment, supporting the transition from descriptive to predictive and prescriptive management strategies.

5.4. Significance and impact

Despite the many challenges involved in the long-term process of digital transformation of marine infrastructure and the environment in areas of vital importance, such a process offers many important benefits. These benefits primarily concern the industry stakeholders operating in these areas, as well as the respective industry sectors in general, which in turn have significant impacts on economic and social development. Another very important benefit is the protection of the environment against the risks involved in the rapid development of marine areas. At the scientific level, significant benefits are obtained for both research and education.

A key enabling factor of the present study is the close collaboration between academia and industry stakeholders. Access to operational marine infrastructure and long-term monitoring data is traditionally restricted due to confidentiality concerns, operational risk, and commercial sensitivity. Through structured collaboration frameworks, these barriers were successfully addressed, enabling the deployment of permanent in-field laboratories and the continuous acquisition of high-quality structural and environmental data under real operational conditions. This collaboration facilitated access to datasets that would otherwise be unavailable to the research community and allowed the integration of advanced monitoring and digitization technologies directly into critical infrastructure.

Through collaboration with the academic and research community, energy stakeholders are able to introduce technological and knowledge advances resulting from scientific research into the market, which may secure significant financial benefits. The major energy stakeholders operating at the Vasiliko Energy Centre, such as VTTV, benefit from the advanced data-driven operation and management approaches towards securing and expanding their productive activity. In addition, the project is expected to have further impact on the energy sector in the near future. The establishment of new energy assets and operations – e.g. liquefied natural gas terminals and floating storage regasification units – is currently under study and development.

Through digital transformation, more efficient and effective solutions for the design, routine operations, and maintenance management of critical infrastructure will be obtained, which will both limit operation costs and increase productivity. Furthermore, it is expected that critical infrastructure will have a higher margin of safety against extreme conditions – including natural hazards, accidental events, and manmade actions. This is particularly important since structural failure of critical infrastructure may have an impact on the economic stability of the country.

Finally, the development of solutions that greatly support environmental sustainability and the safety of developed marine areas is particularly important and will also have substantial significance in terms of social development. In relation to the Vasiliko Energy Centre, for instance, one of the main objectives is to ensure an increased level of safety for the operators and the communities located near this highly congested industrial area. Digitization solutions may involve effective management techniques aimed at optimizing safety monitoring operations, reducing human error, and developing countermeasures.

6. DISCUSSION AND CONCLUSIONS

One of the main objectives of the present study is to promote effective holistic solutions for the management of the rapidly evolving applications related to marine infrastructure and environment, based on the possibilities offered by digital technologies. This involves the digital representation of the physical and functional characteristics of marine infrastructure facilities, along with characterization of the environmental conditions. As the exploitation of the marine environment rapidly increases, in the context of energy industry development and other large-scale applications, the amount of data generated from these activities increases by a large factor. It is therefore becoming extremely important to identify efficient methods of utilizing this data towards optimizing performance, enhancing productivity, minimizing risks, and eliminating hazards.

In collaboration with industry stakeholders, two innovative in-field laboratories have been established in two strategic areas of Cyprus: the Vasiliko Energy Centre and Ayia Napa Marina. These laboratories enable real-time monitoring of key structural and environmental parameters. The former represents an industrial marine environment that involves a substantial number of critical energy infrastructure facilities, while the latter mainly represents a marine environment of commercial and residential activity that has undergone substantial development over the past few years. The purpose of establishing these two in-field laboratories is to collect real-time data from these areas, related to key structural characteristics and environmental conditions, which can underpin the development and integration of digitization tools towards a more holistic approach. The potential cross-fertilization of knowledge, data, experience and understanding obtained from the development and operation of these two in-field laboratories in different coastal infrastructure and environments further enhances the value of this work.

The in-field laboratories consist of high-quality monitoring systems that employ state-of-the-art sensing technologies. The monitoring network provides structural acceleration data, wind speed and wind direction data, water quality data, and wave data. Monitoring devices have been installed at selected locations, either on existing infrastructure or in coastal/offshore areas on the surface or on the seabed. These devices are directly connected to industrial computers to which they transfer the data in real time. One industrial computer is available in each in-field laboratory, installed in the vicinity of the monitoring equipment, and is properly designed to operate in harsh environmental conditions. While the substantial volume of recorded data is temporarily stored on the industrial computers, it is transferred in a relatively short time interval and stored in a central database.

A key component of the real-time monitoring process is the availability of data to interested users in various ways for different applications. Thus, industry stakeholders are provided with valuable information regarding their infrastructural assets and the environment, which they can use to optimize management of their assets and their operations. On the other hand, the EMERGE research group has a large collection of data to use for research purposes. Since the efficient utilization of the data is the ultimate objective of the project, particular attention has been paid to post-processing of data, and to making the data easily accessible to interested users. Important steps in this direction include the development of user-friendly graphical interfaces for easy preview of selected data. Another key step is the generation of automated daily reports to be made available to interested users.

The advancement of knowledge in the subject areas of energy studies and the digitization of marine infrastructure and environment are key objectives of the EMERGE CoE. The vast amount of valuable data generated on a daily basis from the established in-field laboratories forms the basis of efforts in this direction. Research activities are oriented towards the development of innovative data-driven approaches integrated with machine learning methods and advanced analysis tools. These approaches are used to characterize structural and environmental parameters, examine their interplay, and develop suitable prediction methods for nowcasting and forecasting applications. As demonstrated in the present study, the collected in-field data contributed to the development of machine learning models for nowcasting wave height based on structural acceleration and wind data. In addition, the project advances knowledge in seawater quality assessment by demonstrating the significance of key water quality parameters and proposing data interpretation techniques.

The monitoring network system presented in this paper forms the basis of an extensive project with multiple directions and components, each of which may continuously offer possibilities for further study and development. Having appreciated and understood the demands and challenges of this project, and having already established a strong foundation consisting of properly equipped in-field laboratories, the necessary supporting infrastructure, and growing expertise, the project is continuously progressing. The ultimate objective is the development of a holistic digital transformation system for marine infrastructure and the environment. The impact of this project is reflected in significant economic, social, scientific, and environmental developments.

CRediT authorship contribution statement

Marios Koronides: Conceptualization, Data curation, Investigation, Methodology, Resources, Writing – review and editing. **Panagiotis Stylianidis**: Conceptualization, Data curation, Investigation, Methodology, Resources, Writing – original draft. **Constantine Michailides**: Conceptualization, Investigation, Methodology, Resources, Supervision, Visualization, Writing – review and editing. **Toula Onoufriou**: Conceptualization, Investigation, Funding acquisition, Methodology, Project administration, Resources, Supervision, Visualization, Writing – review and editing.

Data availability

Data will be made available on request.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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