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Feroz Khan
University "G. D'Annunzio" of Chieti-Pescara, feroz.chan@unich.it

Agnese Rapposelli
Life Cycle Risk Assessment of a Monopile Offshore Wind Power Plant in Italy: An Interval Type-2 Quantitative Fuzzy FMEA Approach, agnese.rapposelli@unich.it

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Life Cycle Risk Assessment of a Monopile Offshore Wind Power Plant in Italy: An Interval Type-2 Quantitative Fuzzy FMEA Approach

Feroz Khan[1*[0000-0002-0456-3711]] and Agnese Rapposelli[2[0000-0003-0179-9873]]

[1]Department of Management and Business Administration, University "G.D'Annunzio" of Chieti-Pescara, Italy. *Corresponding author
feroz.khan@unich.it
[2]Department of Economic Studies, University "G.D'Annunzio" of Chieti-Pescara, Italy
agnese.rapposelli@unich.it

Abstract. In terms of renewable energy adoption, Italy is making a decent progress by shifting towards biomass, solar and wind to reduce its reliance on fossil fuels. However, a rather new alternative to traditional onshore wind power plant, offshore wind power projects, are becoming more and more popular in Europe. Italy is still in its early stage with only one project realized in the Mediterranean Sea. To foster the growth of these projects it is advised by the European Union to engage in risk assessment methodologies and studies able to provide a smooth transition towards the development of such technologies. In this context, this study is the first one to perform a risk analysis on the only standing offshore wind power plant in Italy. For this purpose, this work uses a rule-based Failure Mode and Effect Analysis (FMEA) approach integrated with the interval type-2 fuzzy Pythagorean. The risks adopted from the secondary literature with the help of experts are based on sustainability factors such as technical, economic, environmental and socio-political ones. The risks are based on the phases of planning, commissioning and operational stages. A total of 27 risks are assessed based on severity, occurrence and difficulty in detection which are subsequently filtered through the 125 rules for more effective outcomes. The risks that are rated to be the most critical ones would then be assessed to provide corresponding risk management strategies.

Keywords: Offshore wind power plant, Risk assessment, Failure Mode and Effect Analysis (FMEA) approach, Interval type-2 fuzzy sets.

1 Introduction

Nowadays countries around the world are shifting towards the adoption of green energy alternatives to avoid greenhouse gas emissions and achieve Sustainable Development Goals (SDGs) set by the United Nations. In essence, Sustainable Development Goal 7 (SDG7) is about the adoption of affordable, reliable, sustainable and modern energy for all. Besides the notion of environmental sustainability, a more pressing concern that has achieved more attention today is that of energy security, especially due to the recent Russian-Ukraine war. The sanctions imposed on Russia have affected the whole world with respect to energy security; Europe has been rather more affected because of its substantial reliance on the natural gas import. However, the flip side is that the so-called energy dependence on Russian gas has rather motivated the European Union (EU) to bring resilience in its energy sector. It is however important that the adoption of newer energy technologies must conform to the standards of European Green Deal and EU targets (2030 energy and climate targets and the 2050 long-term decarbonization goals). A more focused agenda in this regard is supported by the LIFE clean energy transition program to which a budget of around 1 billion Euros has been allocated for the period 2021-2027. This program aims at achieving energy alternatives that are deemed efficient, renewable and climate neutral, thus paving way towards a more resilient EU economy (1). Hence, the constraints and goals mentioned above have encouraged countries like Italy to transition towards the adoption of renewable energy systems.

Italy has a very important standing point with respect to its contribution in the EU economy. In fact, it is the founding member of the EU and is considered the third largest economy with a GDP of $2.058 trillion (2). Energy production and consumption represent very important parameters in gauging the economic development of any country. To achieve energy security and sustainable development, Italy plans to increase its share of renewable energy production to 72% by 2030 and to around 95-100% by the year 2050 (3). This rather ambitious goal is to be achieved through the adoption of wind and solar power plants. After the solar energy, wind energy is the second most suitable alternative to meet the energy demands of Italy. The scenario of wind energy in Italy can be drawn based on the overall picture of Europe. Until 2019, Europe managed to install 183 GW of onshore wind power plants, whereas in the same year the offshore wind power plants capacity was 22 GW. Wind energy in Europe has seen steady growth from 370 TWh to 489 TWh from 2018 to 2022. In 2022, Europe installed a total of 19.1 GW of wind power plants (16.7 GW of which were onshore whereas 2.5 GW were built on offshore foundations). Germany, Sweden and Finland were amongst the countries which built the greatest number of onshore wind power plants, whereas the greatest number of offshore wind power plants were installed in the UK, followed by France (4). Europe intends to install 450 GW of offshore wind power capacity by 2050 (5). Wind energy has been considered a very important resource by European Union achieve the 2050 target of carbon neutrality and contribute substantially to the EU economy especially in providing jobs to the people. However, there are several impediments that still needs to be identified and solved so that offshore wind power plants can be a solid reality. For example, research and development activities needs to be employed for effective transition. Moreover, the offshore maintenance costs are still considered very high which in turn requires higher feed-in-tariffs by the government for the investor to have the minimum profitability (6). Until 2019, Italy installed wind energy capacity of 10.5 GW based on onshore platforms. Most of these plants are installed in Southern Italy because of better wind resource. At present, 20 terawatt of electricity is produced from wind power each year; however, this value is expected to double by the year 2030. The National Integrated Climate and Energy Plan estimates that the onshore wind capacity would reach 18.4 GW by the year 2030, while the offshore capacity is expected to reach 0.9 GW if all the circumstances will be in the favor for the expected 2-3 projects. There are two main uncertain circumstances that could sabotage these projects. Firstly, most of the areas suitable for such projects are in deep marine waters where there are less resources available for installation aims. Secondly, the offshore wind resource in these areas is not considered to be ideal as opposed to countries situated in Northern Europe (7). These along with other technical, economic, socio-political and environmental aspects makes the feasibility of such offshore wind power projects rather challenging. Some of the prominent challenges correspond to long permitting procedures, stringent regulations, challenges and bottlenecks in the supply chain and other environmental concerns such as the possibility of posing a threat to the marine ecosystem. On the other side, there are several advantages for offshore wind power plants that make it as an important alternative to meet the energy demands of Italy and meet its sustainability targets. For example, such power plants do not pose as a visual threat as opposed to onshore wind power plants. Also, newer offshore wind power plants have more capacity factor as opposed to their onshore counterparts. To obtain these advantages from the development of offshore wind power plants, the European Union - through the RELIAWIND consortium - gave grants to European countries to carry out projects able to both identify the risks and provide strategies for the development of offshore wind power plants. Most of these projects employed the Failure Mode and Effect Analysis (FMEA) approach. In this context, Italy benefited of contribution equal to euro 365.826,02 from the European Union to carry out such projects (8). The offshore wind technology in Italy is still in its early stage; hence, we consider necessary to identify the critical linked to offshore wind power plants.

In this framework, it is important to understand that offshore wind turbines are differentiated based on the type of foundation used. The foundation is considered the key component because it affects the safety and the construction cost of the overall project. The different types of foundation include monopile, gravity, tripod, jacket and suction bucket foundations. The foundations are further divided into fixed and floating types. Fixed foundations are mostly used in shallow waters i.e., below 50 m. Such type of foundations includes monopile, gravity, tripod and jacket foundations. New developments in the offshore have made it possible to construct such turbines in even deeper waters with even more capacity. In this context, the present study focuses on the monopile structure wind turbine constructed in Italy. So far Italy has been able to develop only one offshore wind project, named Taranto wind farm and located in the Mediterranean Sea in Apulia. The project is designed based on the monopile foundation and has a total of ten turbine each of which is 3 MW. Since the project was the first of its kind it had to face several legislation hurdles. Also, due to the stringent legislation regarding the development of such projects in Italy, the project had to go through several formalities to obtain the permit amongst many other projects. After the approval phase, the project started in 2021 and was completed in April 2022 for its commercial operation. It can generate 55,600 MWH of clean electricity lighting up a total of 20,000 households. With a cost of $93.467m, it can avoid 730 thousand tons of carbon dioxide (9). This project has paved way for other similar projects. However, a lesson for other projects can be learned by performing a life cycle risk assessment of the Taranto offshore project in Italy. For this purpose, the current work performs an exhaustive literature review for the identification of all the critical risks that might impede an offshore wind power project. The risks are identified based on the sustainability criteria of socio-political, economic, technical, and environmental aspects. The methodology employed is a quantitative type-2 interval fuzzy Failure Mode and Effect Analysis (FMEA) approach. Hence, both primary and secondary sets of data are employed in this study to assess the risks and provide corresponding mitigation strategies for the most critical risks for the development of offshore wind power plants in Italy.

The paper is organized as follows. Section 2 introduces the literature review, Section 3 discusses the data used, Section 4 presents the methodology adopted and Section 5 concludes.

2 Literature Review

Offshore wind power plant is still a new concept in most of the world. Therefore, most risk assessment studies in this regard concern onshore wind power plants. According to statistics on wind power accidents, most of the failures and accidents take place during the construction and operations stage (10). Right now, Europe is the leading offshore wind energy market. The European Union has promoted regulations that aids these countries to manage the risk pertaining to the offshore wind energy deployment. The risks pertaining to offshore wind power plants are quite different from the one's faced by the onshore systems. Geographic conditions also have a lot to do when it comes to the variances in the risks faced by such systems. For example, countries in Northern Europe have better wind resource but they have their own challenges and have different dynamics than the ones faced by countries like Italy (11). Due to the nascency of offshore technology, sustainability factors such as technical, environmental, socio-political economic aspects are much debated in Europe. The high cost of offshore technology as opposed to onshore systems is still considered as a barrier. From the technical point of view, technological innovations have to step in to make the offshore wind system fit for the harsh offshore conditions. It is important to understand that most of the current offshore technology is an adaptation of the existing onshore technology. The technology has a harmful impact on the marine life. However, the results of such environmental impacts are mixed which needs further studies and time to actually understand the true nature of the problem (12). Offshore wind turbines have to be designed based on the meteorological conditions of a region e.g., Europe waters have different dynamics than the waters in north America. The designing of the offshore systems in this regard should be able to harvest huge amounts of energy in the far-off oceans. Moreover, such technological innovations should come up with floating foundations that are economically friendly with respect to onshore wind power plants (13). The operations and maintenance phases are also considered to be crucial in the determination of levelized cost of electricity. In particular, maintenance activities are considered to be more crucial because they drive the overall efficiency, safety, profit margins and sustainability of the project (14). The different type of offshore wind farm foundation has varying types of risks during the construction period. Therefore, risk assessment pertaining to a particular foundation type should be formally carried to provide mitigation strategies accordingly. Most of the risks corresponding to service periods include ship collision, fatigue damage, scouring and corrosion damage. These risks are going to get worse in adverse environmental condition and therefore effective risk management tools need to be promulgated for risk mitigation (15).

Decision-making represents an important part of risk assessment studies. The assessment of risks and the provision of mitigation strategies are considered to be an intricate and complex task that requires robust decision-making tools. To deal with this problem, the Fuzzy Analytic Network Process (FANP) has been adopted to analyze various aspects of offshore wind projects. The criteria in this case have to address risks related to the safety, cost, viability and return on the project. The case of a 2 MW project is taken as a model to validate the methodology for the determination of risk management strategies (16). In another case, a dedicated methodology is designed to prioritize the risks associated with the accidents corresponding to collisions between ships and wind turbines during maintenance activities. The greatest number of accidents in this case corresponds to the maintenance activities with respect to corrective actions such as replacement of a component (17). To improve the system reliability of offshore wind farm and decrease failure and downtime of the system, the use of a three process Markovian approach is applied to cater to the shortcomings of an ordinary Fault Tree Analysis (FTA). The model integrates the FMEA approach to identify failure modes and their common causes through the help of experts and literature analysis (18). A more rational approach based on fuzzy FTA is adopted to carry out a risk management approach for a floating offshore wind turbine. The analysis is carried out for five subsystems consisting of supporting structure, pitch and hydraulic system, gearbox, generator, and auxiliary systems. This approach is able to involve both qualitative and quantitative sets of data. The qualitative data are involved for risk identification purposes, while the quantitative ones involve the determination of failure rates through the incorporation of trapezoidal fuzzy numbers (19). The fuzzy set theory is able to capture ambiguity and complexity during the decision-making process which makes it essential to be utilized for determining probabilities on assessing risk assessment for offshore maintenance scheduling problems. An optimal scheduling of maintenance activities can reduce environmental and safety risks with regards to offshore wind farms (20).

A review of literature regarding offshore wind farms suggests that two types of methodology are applied with respect of risk analysis i.e., qualitative and quantitative. The qualitative methods include studies such as failure mode analysis, graphical and tree analysis, and in some cases hazard analysis which comes with less of computation and complexity. The quantitative sets of data are more complex and require large amounts of data; however, these approaches are mostly based on analytical and statistical methods, such as Bayesian networks, optimization based on reliability design models, strategies pertaining to data gathering and multivariate analysis. The recent literature is more focused on the application of tools that address uncertainty, for example the fuzzy set theory. Moreover, the application of sensitivity analysis tools should advance further to optimize the design and operation of wind turbine (21). Presently, most of the literature is focused on the FMEA approach and its improved versions to tackle risk assessment studies. The improved versions of FMEA are designed to tackle the shortcomings of the standard FMEA (15). The standard FMEA approach is not able to provide practical and flexible results because the risks are yielded with similar Risk Priority Numbers (RPN). For example, a more improved version of FMEA involves the determination of three deciding factors for calculating the RPN ranking. In this case, the three parameters involve subjective ranking (RPN), calculation of objective ranking (i.e., involving economic aspects), and the semi-subjective ranking that is a mix of the aforementioned elements. It is found that some risks are unavoidable and cause failures pertaining to devices causing fatigue, wear and tear, and corrosion. Besides, environmental related risks such as string winds are considered to be the most destructive towards the support structures. Moreover, the failure of mooring lines is considered to be most detrimental (22). Data availability with respect to downtime and failure rate is sometimes a challenging task which makes the FMECA (Failure Mode, Effects, and Criticality Analysis) approach rather challenging. The FMECA is an extension of the traditional FMEA but with criticality ranking that allows to determine counter measures. The FMECA approach can be enhanced by determining the threshold of the risk making the levels of risk more evident for countering the risks (23). However, since the concept of offshore wind turbines is still new in Europe, gathering such data is a challenging task which can be tackled through the introduction of rule-based approach that can counter the subjectivity introduced due to the engagement of decision-makers and experts. When decision-makers are involved, it calls for tools that can deal with the complex nature of the decision-making process. The goal of such tools is to decrease the levels of subjectivity and ambiguity. To achieve such kind of robustness, the use of extended fuzzy sets makes more sense as opposed to traditional fuzzy sets (24). The advent of such an amalgamation of both qualitative and quantitative measures can be very useful for carrying life cycle risk analysis for the first offshore wind power plant in Italy.

The literature does not address any study that performs the life cycle risk assessment of an ongoing offshore wind project in Italy. There is only one study related to risk analysis but it is based on onshore wind power plants in Italy. Also, the objective of the study only focuses on the occupational safety of workers during the operation period (25). Apart from Italy, the literature does not support any study that engages in the determination of a life cycle risk assessment approach for a monopile foundation offshore wind power project. A life cycle risk assessment approach though exists for an offshore wind turbine in China with suction bucket foundation (26). Risk analysis is considered to be a challenging task in the offshore wind industry as well as an important tool for the attainment of renewable energy targets. Even if decision-making is considered to be an important parameter for determining mitigation strategies, the literature is rather scarce based on the aforementioned subject (27). With respect to the methodology, studies on the application of FMEA pertaining to floating offshore wind farms correspond to the integration of a traditional FMEA with reliability index vector to find correlation between failure modes and their impact on failure (28). Another similar study, conducted in the context of UK, incorporates the fuzzy set theory for tackling the notion of uncertainty of subjective factors (29). Another modified version of such methodology integrates traditional FMEA with the provision of cost consequence of each failure, thus addressing both qualitative and quantitative data (30). A more recent advance on the methodology is related to the development of a two stage FMEA approach that identifies the critical failure modes of each component which in the second stage are evaluated based on a cost and risk-based index (31). The rule-based methodology adopted in this study has several advantages that previous studies have not taken into account. Firstly, the extended fuzzy sets based on type-2 interval Pythagorean sets can capture more effectively complexity and subjectivity of the decision-makers. The flaws of traditional FMEA approach pertaining to similar RPN ranking is solved through the use of a rule-based approach. The rules are designed to both reduce subjectivity and provide more practical results. Distinctive linguistic variables and ratings are designed for both input (i.e., the calculation of occurrence, severity and difficulty in detection) and output variables (i.e., the calculation of RPN). This particular approach has been applied for the evaluation of risks pertaining to maritime transportation (32). However, this study applies the same approach for carrying out the life cycle risk assessment of an offshore wind power plant in Italy.

3 Data

As mentioned in the Introduction, the focus of this study is to assess the life cycle risk assessment of the first offshore wind power plant in Italy. The project, named Beleolico, was built near the Taranto harbor, in the Mediterranean Sea. It comprises 10 wind turbines, each with a rating of 3MW. The name of the model is MySE 3.0-135, sourced from a company called MingYang Smart Energy, owned by a Chinese company. The project is laid on the monopile foundation platform. The specification sheet of the wind turbine adopted s given in Table 1.

Table 1. Specification sheet of MySE 3.0-135 Wind Turbine (source: (33))

Model	Unit	MySE3.0-135
Rated power	kW	3000
Designed wind zone class		IIIB
Cut-in wind speed	m/s	3
Rated wind speed	m/s	10.2
Cut-out wind speed	m/s	20
Designed lifetime	year	20
WTGS operating temperature	℃	-30～+40
WTGS survival temperature	℃	-40～+50
Adaptable environment	Normal temperature, low temperature, ultra-low temperature, plateau and coast, anti-typhoon, offshore	

The monopile is the most widely used offshore foundation, characterized by a simple structure. The foundation has piles of steel pipes with diameter of 3.5-6 m and length of 30-40 m. The construction phase is the most challenging offshore foundations especially during the piling process. The steel pipes must have enough stiffness to wind stand the weight of turbine and piling process (34). The construction of monopile foundation platforms involves four phases. The first two phases include onshore manufacturing and loading of materials on the dock; they are carried out on land and are less risky. The other two phases focus on the transport of the equipment in the sea and the process of assembly and installation. These last two phases are riskier because of complex and adverse sea conditions. Some of the prominent risks associated with the construction phases include sliding of the pile, refusal of the hammer and crane damage. The operation steps of monopile structured wind turbines also face rough sea conditions. During the service periods the accidents are very common which results in huge economic losses, failures and down time. Some of the prominent risk during service and operation periods include scouring, corrosion, fatigue failure and collisions (15).

In order to carry out the risk assessment for the first offshore wind power plant in Italy, this study considers four phases of the project which include planning, construction and operations periods. The data collection process comprises two stages. The first stage focuses on the collection of risks that are most prominent for the development of offshore wind power plants, while the second stage corresponds to the involvement of experts to rate those risks. The risks from the secondary literature are gathered based on the metric sustainability. These metrics include technical, economic, environmental and socio-political aspects. These aspects are considered very important for the development of such projects. For this purpose, an exhaustive literature review is conducted to determine the most relevant and critical risks based on the dynamics of the renewable energy scenario and geography of Italy. The type of documents reviewed and analyzed are original article, review articles, conference proceedings, reports, unpublished thesis and other private websites. For scientific articles, Google Scholar and the Scopus database was referred to. After going through all the documents, a total of 40 risks under the metrics of sustainability were gathered. The risks that were most repeated or rephrased were removed from the first list thus leaving a total of 33 risks for further analysis. The next step engaged a panel of experts to review the risks and highlight the ones that were considered the most critical in the context of Italy. Two experts having expertise in the same sector were involved, and they helped in removing redundancy amongst the list of risks. Finally, the mini-Delphi approach was applied to help in finalizing the risks for carrying out the life cycle risk assessment. As a result, the total number of risks went down to 27. For example, risks such as “public perception or acceptability” were not considered essential or critical because such risks are more prevalent to onshore wind power plants. The latter might face criticism for factors such as noise generation or aesthetic issues. Amongst all the available risks, technical risks were considered the most critical from the Italy’s perspective; most of the risks are therefore associated with technical aspects. The finalized list of risks and their corresponding references are listed in Table 2.

Table 2. Possible risks faced by offshore wind power plants in Italy

Type of risk	Risks	Definition	References

Technical	Supply chain disruptions and bottle necks	Most of the offshore equipment are imported from countries outside Europe, thus creating challenges during procurement stages.	[35-37]
	Fatigue damage	External forces on the support structure of the turbine result in fatigue. The most prone structural components in this case are drag on the tower, transition piece, nature of the soil, external diameter and water depth.	[38-40]
	Pile driving risk	The process of forcing the pile into the sea land may cause noises, pile refusal or hammer refusal.	[41-43]
	Marine transportation risk	Risks of accidents or costs of diversion.	[44-47]
	Crane accidents	Accidents during maintenance.	[15, 48]
	Scouring	The movement of sand from the foundation due to strong waves or currents.	[49-51]
	Corrosion damage	Corrosion of the turbine structure and blades due to the harsh sea and environmental conditions.	[52,53,38]
	Generator failure	The mechanical and electrical components of the plant that is responsible for converting mechanical into electrical energy. The efficiency of the turbines is highly reliant on the reliability of the generator. Major components include rotor, bearings and stator.	[54-56]
	Gear box failure	Gradual reduction of components such as gear or bearing due to lack of timely maintenance and lubrication.	[57, 58]
	Lubricants and oil leakage risk	Leakage of oils and lubricant due to breakdown of gearbox, generator etc. (a turbine contains about 400 l of gearbox oil and 25 kg grease (35)).	[35]
	Pitch and yaw subsystem failure	A wrong pitch and yaw angle may lead to unbalanced blade rotation and lower efficiency.	[60, 61]
	Cyber attach	An unauthorized access to critical infrastructure equipment disrupting the flow of energy supply.	[62-64]
	SCADA system failure	False alarms or error in the system can create confusion for the operators in mitigating the actual fault.	[65-67]
	Submarine cable damage accidents	Damages caused as a result of jacking up, damage caused between anchors, and cable kinking etc.	[68-70]
	Blade failure	Cracks and fractures, failure of motor or pitch bearing, hit by birds.	[71, 72]
	Failure risk of tower, transition piece and monopile	These are the major structural components that are responsible for keeping wind turbine intact. Failures can occur	[73-75]

		because of stresses, grout failure, or scouring the case of the monopile itself.	
	Site selection risk	Risks relative to health and safety, economic feasibility, consenting issues, and grid connections.	[76-78]
Environmental	Marine ecological damage	Damage to the marine life especially due to noise generation and vibration during the construction and operation phases.	[59,79,80]
	Barrier effect	Obstruction due to flying birds.	[81-83]
	Natural disasters	Risks pertaining to typhoons, lightning, sea waves and earthquakes.	[84-86]
Socio-political	Lack of skilled technicians - availability risk	Lack of technical experts.	[87, 88]
	Occupational health hazard	Noise, electromagnetic radiations and physical stress.	[89, 90]
	Legislative delays	Lengthy and intricate bureaucratic procedures for permits purposes.	[91, 92]
	Unclear and unstable feed in tariff policy	Varying and unclear policies and subsidies from the government regarding offshore wind projects.	[93, 94]
Economic	Challenges in the determination of LCOE (feasibility analysis)	Complex nature of offshore wind power projects makes the calculation rather challenging	[95, 96]
	Investment decision and unstable revenue risk	High operations and management costs and uncertainty related to harsh offshore condition can make the project costly thus yielding in lesser revenue or other force majeure events.	[97, 99]

4 Methodology

The Failure Mode and Effect Analysis (FMEA) approach employed in this study is a famous tool used to tackle risks in the best possible manner. It was first applied in the aerospace sector and then in various other sectors and industries. Its aim is to determine and assess failures that might impact the systems at hand by determining the RPN number given by the product of probability of failure occurrence, severity of the risk and capability (detection) of the risk, as shown in equation 1 below.

$$RPN = O \times S \times D \tag{1}$$

The problem associated with the determination of RPN numbers is that basic Likert scale leads to similar results for the risks. To remove the notion of subjectivity, this problem is dealt with fuzzy sets. However, traditional fuzzy sets are not powerful enough to capture the uncertainty and deal with ambiguity with respect to the data collection process from the experts. Therefore, a more rational approach is represented by the application of more intricate fuzzy sets. For this purpose, this study proposes the use of interval type-2 fuzzy sets thus handling uncertainty and subjectivity in a more robust manner (24).

4.1 Interval Type-2 Fuzzy Sets

The main quality of such sets is represented by their ability to hold the properties of the traditional fuzzy sets. This means their membership functions are the fuzzy sets itself. The original concept of type-1 fuzzy sets was introduced by Asger Zadeh in 1965; however, after facing criticism for their inability to capture uncertainty, Zadeh introduced in 1975 an extended version known as type-2 fuzzy sets (36), which is employed in real world problem solving. The sets have a greater number of degrees of freedom and their calculations are more rational making them easier to comprehend (37). To better understand them, some of the basic definitions of the interval type-2 fuzzy sets are given below (38).
Definition 1.
A type-2 fuzzy set can be denoted by $\tilde{A}$, the membership function ($\widetilde{u_A}$) of which denotes a fuzzy set (39).

$$\bar{\bar{A}} = \{((x,u),\ \widetilde{u_A}\ (x,u)) | \forall\ x \epsilon X, \forall\ u\ \in J_X \subseteq [0,1], 0 \le \widetilde{u_A}(x,u) \le 1\} \tag{2}$$

In the above equation an interval of [0, 1] is denoted by J_X. Besides, the type-2 fuzzy set of $\tilde{A}$ has its own standing:

$$\bar{\bar{A}} = \int_{x\,\epsilon\,X} \int_{u\,\in J_X} \widetilde{u_A}(x,u)/(x,u) \tag{3}$$

The x in equation 2 denotes the primary variable in the X domain, whereas the u denotes the secondary variable for the relationship $x \epsilon X$ in interval $[0,1]$. Moreover, J_X symbolizes the primary membership function of x, whereas $\widetilde{u_A}(x,u)$ indicates the secondary membership function of the set $\tilde{A}$. The symbol $\int \int$ in this case indicates a union of the acceptable values of x and u.
Definition 2.
The special case of type-2 fuzzy sets which does not provide further information on the sets is expressed with the following equation:

$$\bar{\bar{A}} = \int_{x\,\epsilon\,X} \int_{u\,\in J_X} 1/(x,u), \tag{4}$$

where $J_X \subseteq [0,1]$.
Definition 3.

Different types of fuzzy sets such as triangular, Gaussian and trapezoidal ones are present in the literature; this study uses the trapezoidal interval type fuzzy sets. The characteristic of type-2 fuzzy sets is that the membership functions of such sets correspond to the type-1 membership function. These type-1 membership functions are characterized by upper and lower membership functions respectively. Type-2 fuzzy sets employed in this study can be better understood with the help of the explanation of the reference points and heights of the aforementioned membership functions.
A trapezoidal type-2 fuzzy set can be denoted by $\tilde{A}_i$ as follows:

$$\overline{\overline{A}}_\imath = (\tilde{A}_i^U, \tilde{A}_i^L) = (a_{i1}^u, a_{i2}^u, a_{i3}^u, a_{i4}^u;\ h_1\left(\tilde{A}_i^U\right), h_2\left(\tilde{A}_i^U\right)),$$
$$(a_{i1}^l, a_{i2}^l, a_{i3}^l, a_{i4}^l;\ h_1\left(\tilde{A}_i^L\right), h_2\left(\tilde{A}_i^L\right)) \tag{5}$$

where $a_{i1}^u, a_{i2}^u, a_{i3}^u, a_{i4}^u; a_{i1}^l, a_{i2}^l, a_{i3}^l, a_{i4}^l$ are the reference points for the type-2 fuzzy sets, and $H_j\left(\tilde{A}_i^U\right)$ indicates the membership term for the variable $a_{i(j+1)}^U$ in the upper trapezoidal membership function such that $\tilde{A}_i^u$, $1 \leq \sigma \leq 2$. On the other hand, $H_j\left(\tilde{A}_i^L\right)$ indicates the membership term for the variable $a_{i(j+1)}^L$ in the lower trapezoidal membership function such that $\tilde{A}_i^L$, $1 \leq \sigma \leq 2$. The membership function of such sets is shown in Figure 1.

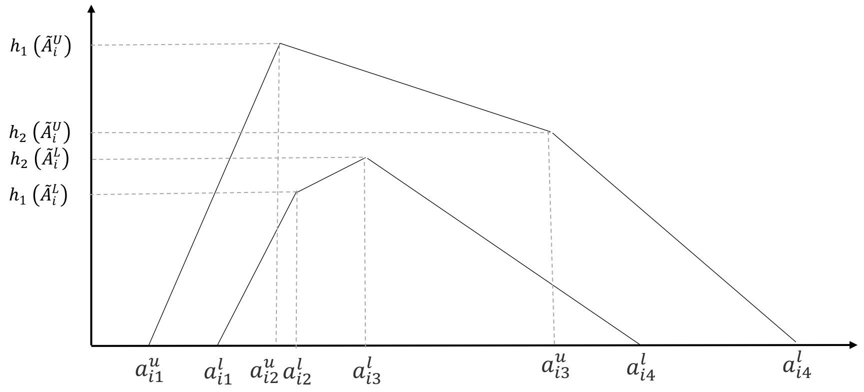

Fig. 1. Membership function for interval type-2 fuzzy sets

4.2 Integration of Type-2 Fuzzy Sets with FMEA Approach

To compensate the drawbacks of traditional type-1 fuzzy sets and traditional FMEA approach, their integration has been highlighted in the literature through its usage to perform risk assessment for steam valve system (40). It has been further validated through its application for the railway infrastructure projects (41), along with the aerospace electronic manufacturing projects (42). The rule-based quantitative risk assessment approach adopted in this study has been applied for performing risk assessment for oil spill problem (24). This study uses the same approach for its application in an existing offshore wind sector in Italy making it the first study of its nature with respect to the context in question. The approach consists of six steps, described below.

Step 1. For data gathering purposes, the linguistic terms and their corresponding numbers are designed for both inputs and outputs. The linguistic terms listed in Table 3 can be used to rate the three inputs i.e., occurrence, severity and difficulty in detection, whereas the determination of outputs can be achieved through the ten linguistic variables presented in Table 4.

Table 3. Input fuzzy numbers for the determination of occurrence, severity and difficulty in detection

Linguistic value	Associated numbers
Almost none	((0;0;0;0,1;1;1), (0;0;0;0,05;0,9;0,9))
Low	((0,1;0,3;0,3;0,5;1;1), (0,2;0,3;0,3;0,4;0,9;0,9))
Medium	((0,4;0,6;0,6;0,8;1;1), (0,5;0,6;0,6;0,7;0,9;0,9))
High	((0,8;0,95;0,95;1;0;0), (0,9;0,95;0,95;1;0,9;0,9))
Very high	((0,9;1;1;1;1;1), (0,95;1;1;1;0,9;0,9))

Table 4. Output fuzzy numbers for the determination of RPN

Linguistic terms	Associated numbers
None	((0;0;0;0.1;1;1), (0;0;0;0.05;0.9;0.9))
Very low	((0;0.1;0.1;0.3;1;1), (0.05;0.1;0.1;0.2;0.9;0.9))
Low	((0.1;0.3;0.3;0.5;1;1), (0.2;0.3;0.3;0.4;0.9;0.9))
High low	((0.2;0.4;0.4;0.6;1;1), (0.3;0.4;0.4;0.5;0.9;0.9))
Low medium	((0.3;0.5;0.5;0.7;1;1), (0.4;0.5;0.5;0.6;0.9;0.9))
Medium	((0.4;0.6;0.6;0.8;1;1), (0.5;0.6;0.6;0.7;0.9;0.9))
High medium	((0.5;0.7;0.7;0.9;1;1), (0.6;0.7;0.7;0.8;0.9;0.9))
Low high	((0.7;0.9;0.9;1;1;1), (0.8;0.9;0.9;1;0.9;0.9))
High	((0.8;0.95;0.95;1;0;0), (0.9;0.95;0.95;1;0.9;0.9))
Very high	((0.9;1;1;1;1;1), (0.95;1;1;1;0.9;0.9))

With regard to the rule-based approach, in this study a total of 125 rules are developed based on the products of 5 fuzzy numbers for severity, 5 for occurrence and 5 for difficulty in detection. These 125 fuzzy rules make our study distinctive making its results more robust. These rules can be understood from the following examples:

Rule # 1: the risk is considered to be “None” if all the three input variables are rated with “Almost None”.

Rule # 100: on the other hand, the risk is considered to be “Very High” if the three input variables are rated as “High”, “Very High” and “Very High” respectively.

Step 2. This step involves the role experts where their judgment is required to rate the risks based on the linguistic variables in Table 3. Each risk is rated based on occurrence, severity and difficulty in detection. The output of each risk is evaluated based on output linguistics variables given in Table 4 through the aid of 125 rules.

Step 3. The linguistic variables in the second step are subjected to the conversion to their corresponding fuzzy numbers.

Step 4. The average of the responses is obtained through the application of equation 6. This equation helps in obtaining a single evaluation matrix based on the number of experts involved.

$$\bar{\bar{f}}_{ij} = \tilde{f}_{ij}^{1} + \tilde{f}_{ij}^{2} + \cdots + \tilde{f}_{ij}^{k} / k. \tag{6}$$

where $\tilde{f}_{ij}$ represents the interval function where $1 \leq i \leq m, 1 \leq j \leq n, 1 \leq c \leq k$. The k x represents the experts involved. Also,

$$\bar{\bar{f}}_{ij} = (a_{i1}^{u}, a_{i2}^{u}, a_{i3}^{u}, a_{i4}^{u};\ h_1\left(\tilde{A}_i^{U}\right), h_2\left(\tilde{A}_i^{U}\right)), (a_{i1}^{l}, a_{i2}^{l}, a_{i3}^{l}, a_{i4}^{l};\ h_1\left(\tilde{A}_i^{L}\right), h_2\left(\tilde{A}_i^{L}\right)) \tag{7}$$

Step 5. The defuzzification of the fuzzy numbers is carried out using the extended center of area (COA) method (43). Equation 8 below is used to allocate singular weights to the risks (i.e., the RPN score):

$$\mathrm{COA}(\bar{\bar{W}}_j) = ((a_{i4}^{u} - a_{i1}^{u}) + (h_1\left(\tilde{A}_i^{u}\right) \times (a_{i2}^{u} - a_{i1}^{u}) + h_2\left(\tilde{A}_i^{U}\right) \times (a_{i3}^{u} - a_{i1}^{u}))/4 + a_{i1}^{u} + ((a_{i4}^{u} - a_{i1}^{u}) + (h_1\left(\tilde{A}_i^{u}\right) \times (a_{i2}^{u} - a_{i1}^{u}) + h_2\left(\tilde{A}_i^{U}\right) \times (a_{i3}^{u} - a_{i1}^{u}) + a_{i1}^{l})4 + a_{i1}^{l})/2 \tag{8}$$

5 Conclusion

The installation of offshore wind power plants is a challenging task which has several technical, economic, environmental and socio-political risks. Offshore technology is still in a development phase; it is therefore important to determine and assess the risks that might impede the development of further projects. Italy is a new adopter of such technology and needs a facilitating framework for its upcoming projects for smooth transition towards the alternative energy facility. For this purpose, the current study uses a risk management tool known as interval type-2 fuzzy sets to perform risk analysis of the only standing offshore wind power plant in Italy, near the port of Taranto. Through an extensive and exhaustive literature review this work gathers all the possible risks based on the geographical and bureaucratical dynamics of Italy. These risks are further assessed - based on their severity, occurrence and difficulty in detection - from a group of experts belonging to the company that constructed the offshore wind power plant. Moreover, the risks rated with the help of experts are subjected to 125 rules to further screen them and give new objective rating to them. The resultant risks are de-fuzzied and the final RPN ranking is yielded as a result. The final ranked risks are further evaluated to provide corresponding risk management strategies. Based on the results obtained, relevant policy actions are provided to make future offshore wind power projects more profitable.

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