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RESEARCH ARTICLE

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UXO and environmental risk factors impacting EOD operations in German waters

Torsten Frey

DeepSea Monitoring Group – Division of Marine Biogeochemistry, GEOMAR Helmholtz Centre for Ocean Research Kiel, Kiel (Germany)

Correspondence
Torsten Frey, DeepSea Monitoring Group – Division of Marine Biogeochemistry, GEOMAR Helmholtz Centre for Ocean Research Kiel, Wischhofstraße 1–3, 24148 Kiel (Germany) Fax: (+49) 431 600-2805.
Email: tfrey@geomar.de

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Abstract

This article presents risk factors that are associated with the handling of unexploded ordnance (UXO) during explosive ordnance disposal (EOD) operations in German waters. The construction of offshore wind parks and the German immediate action program are expected to increase the number of EOD operations. Existing literature and guidelines do not offer a structured and reproducible framework for assessing EOD risk. To fill this gap, a network of EOD risk factors was developed by means of a literature review and validation via expert consultation. The study was scoped to "personnel and equipment at the EOD location" as the risk receptor and "undesired detonation" as the undesired event under investigation. Factors are subdivided into UXO factors that depend on the object that should be handled and factors that describe the object's surrounding environment. While the former can be researched by an EOD expert, the latter must be measured on site or acquired from a model. Each of these factors contributes to risk, some directly and others indirectly via other factors. The complexity of the resulting network, with its 33 factors, demonstrates the need for a reliable and reproducible model to quantify EOD risk. Its purpose is not to replace EOD experts but to aid them in their decision-making process. Such a tool can provide valuable support for the high-cost and high-risk EOD operations.

KEYWORDS
explosive ordnance disposal (EOD), offshore UXO, risk assessment, risk factors, undesired detonation

1 | INTRODUCTION

The removal of unexploded ordnance (UXO) is an activity that occurs regularly in German waters and worldwide. The vast and rapid construction of offshore wind parks in the German exclusive economic zone [1] can be a driver for an additional increase in explosive ordnance disposal (EOD) operations in the upcoming years. A recent initiative to conduct a feasibility study and initiate an immediate action program to deal with the 1.6 million tons of munitions at dump sites in the German North and Baltic Seas

Abbreviations: EOD, Explosive Ordnance Disposal; ROV, Remotely Operated underwater Vehicle; UXO, UneXploded Ordnance; RE, relative effectiveness.

demonstrates the political will to approach the issue of UXO on a greater scale [2]. If this program is perpetuated as a regular activity, even more EOD operations will take place.

Even though it takes place under somewhat controlled circumstances, EOD is a high-cost and high-risk activity [3]. Once a UXO object is found and identified, the decision on how to proceed becomes immanent. For their decisions, EOD experts rely on research in historic documents on the respective UXO type and years of experience in the field. Surprisingly, neither the academic literature nor existing guidelines on EOD provide a framework on how to assess the risk of handling UXO in a structured and reproducible way. The UXO risk assessment methods that already exist do not deal with the risk during EOD to which employees and equipment are subjected.

Currently, risk assessment is inherently included in the decision-making process of EOD experts. They investigate a number of properties of the UXO object and evaluate whether it is safe to handle, safe to transport, or not. However, a well-documented, structured risk assessment is amiss. Such a structured approach cannot replace experts with many years of experience who have an on-site impression of the UXO object and the surrounding environment. However, it can assist them in gaining reproducible assessment results that are independent of fatigue, repetitiveness, lack of focus, and personal mood.

This paper presents the findings of a first attempt to close this gap. Through a process of literature review and expert consultation, a network of factors that determine EOD risk was developed. The next section introduces the reader to the research method by defining the scope of this study and explaining how the risk factor network was produced. Section 3 describes each of these risk factors and explains how they interrelate. Finally, the ways in which the factors contribute to risk are stressed.

2 | METHODS

The identification of the risk receptor and the undesired event are central to a risk assessment. These are described in 2.1. Next, the causes, i.e., the pathways, that can lead up to the undesired event as well as those that determine the effects must be analyzed [4]. The workflow of this cause and consequence analysis is described in 2.2.

2.1 | Scope of the risk assessment

There are numerous terms and acronyms that classify legacy explosive ordnance. The most commonly used term is unexploded ordnance (UXO), which the United Nations distinguishes from abandoned explosive ordnance (AXO). While the former was “primed, fused, armed, or otherwise prepared for use and used in an armed conflict” [5], the latter was “left behind or dumped by a party to an armed conflict” [5]. The term explosive remnants of war (ERW) combines UXO and AXO [5]. In addition, the term discarded military munitions (DMM) is used in the United States to refer to munitions that were never used in combat but were “abandoned without proper disposal or removed from storage” [6]. In this publication, the acronym UXO is used for all legacy explosive ordnance in German waters since it is the most commonly used in academic literature.

In the literature, numerous approaches to assessing UXO risk can be found e.g. [7, 8, 9, 10]. However, none of these approaches address the risk during EOD operations. The purpose of this paper is to describe and define the UXO and environmental factors that affect the risk during the actual handling of UXO under water. According to the “Quality Guideline for Offshore Explosive Ordnance Disposal”, this concerns the three processes of “underwater transfer”, “in situ destruction”, and “recovery” of UXO [11]. These operations are henceforth referred to as “UXO handling”. All other processes that are part of EOD, such as the historical survey, technical survey, or investigation of target points, are not addressed here.

An important decision that stands at the beginning of a risk assessment is that of defining a risk receptor. Receptors are natural, physical, or socio-economic values that are potentially exposed to risk [12]. They can be people, property, communities, infrastructure, the environment [13] or parts thereof. Receptors that can likely be affected by a detonation during UXO handling can be people (crew, divers, and passengers), equipment (vessels and infrastructure), the natural environment (marine mammals, birds, other fauna, and habitats), and even historic sites (shipwrecks) [8]. The general public and uninvolved people in the vicinity of the operation may be receptors as well. Since this paper deals with EOD risk, it was decided that the “personnel and equipment at the EOD location” should be the risk receptor under investigation.

When preparing a risk assessment, it is also necessary to identify so-called undesired events. A very general classification of undesired UXO events is the distinction between (I) direct physical contact, (II) contamination, and (III) detonation [14]. The contamination of the marine environment and the undesired detonation are the two events that may occur due to UXO handling. As discussed in section 3, this paper focuses on the handling of conventional (i.e., explosive) UXO and does not discuss objects that contain chemical warfare agents (CWA). For conventional UXO, the negative consequences of the contamination do not usually affect the personnel and equipment at the EOD location. The undesired detonation, on the other hand, may occur during UXO handling and have an immediate impact on the risk receptor. It is therefore selected as the undesired event. It should be noted that, for over twenty years, no undesired detonation was reported during EOD operations in the marine environment in Germany. Nevertheless, assessing the risk that is related to UXO handling is advisable given the expected increase in EOD operations in the near future (see 1).

The undesired detonation must be distinguished from the intended in-situ destruction that may take place as a regular process during EOD. If a UXO object is not safe to handle, it is possible that in-situ destruction is unavoidable. However, in the event of such planned detonations, the risk receptors will be at a safe distance. Still, an undesired detonation can occur in preparation for an in-situ destruction.

The next step is the analysis of the causes that can lead to the undesired event as well as the consequences that may arise from it [4]. This method that was used for the analysis is described in 2.2. Section 3 discusses the findings on the individual risk factors that relate to the UXO and to the surrounding environment. Subsequently, they are assembled into a network, showing their interdependencies.

2.2 | Cause and consequence analysis

To provide structure to the creation of the risk factor network, a list of factor dependencies related to offshore UXO was produced by means of a literature study. This process yielded a directory of over 250 factor dependencies (including duplicates), each of which consisted of two or more factors. Factors were the properties of UXO, the environment, and EOD methods.

The factor dependencies were used to produce an initial network of 104 factors. While not all previously listed connections were included, the network still showed the interconnectedness of the many different factors and illustrated the complexity of the UXO problem. However, this factor network could not be used for risk assessment. For some factors, the amount of available literature turned out to be insufficient to reliably include them in a risk assessment. Furthermore, since the network was purely based on a literature review without corrective measures by the author and a revision by experts, the level of detail throughout the initial network varied significantly. Nevertheless, it served as a starting point for the development of a risk factor network. Next, a significant number of factors were deleted from the network, and it was redesigned to be directed at "UXO handling", "undesired detonation" as the undesired event, and "personnel and equipment at the EOD location" as the risk receptor.

An expert workshop was conducted as a means to validate the network. It was attended by nine experts. Seven of them held a certificate of competence per § 20 SprengG (German Explosives Law) [15] or a similar certificate issued internationally or by the military. Of the other experts, one was invited due to their expertise in EOD risk management and the other due to their expertise in explosive materials. The goal of the workshop was to validate the existing risk factor network and adapt it according to the experts' comments. Attendants were asked to identify both irrelevant and missing factors and comment on the relationships between the factors as displayed in the model. After the workshop, the network was updated in accordance with the experts' input. The resulting factor network is shown in Figure 1.

3 | RESULTS AND DISCUSSION

This section introduces each of the risk factors that were identified during the workflow that was outlined in 2.2. Some of them are merged into one subsection to improve readability. All factors are combined into a risk factor network, which is presented in 3.3. To make the risk factor network and a future risk assessment manageable, it was necessary to add some additional scope.

First, it was decided to limit the discussion to German waters (i.e., territorial waters and the EEZ). Germany is currently implementing an immediate action program on EOD in its national waters, which offers an opportunity to design a risk assessment method that can provide meaningful support to upcoming EOD work. The following descriptions of risk factors will at times resort to reports from other countries if they contain knowledge that is relevant to the study at hand.

Secondly, the large majority of UXO that can be found in the German waters originates from combat during WWI and WWII and from dumping activities during the wars and thereafter [16]. It is, therefore, feasible to define a scope for UXO that entered German waters between 1914, which marks the beginning of WWI, and

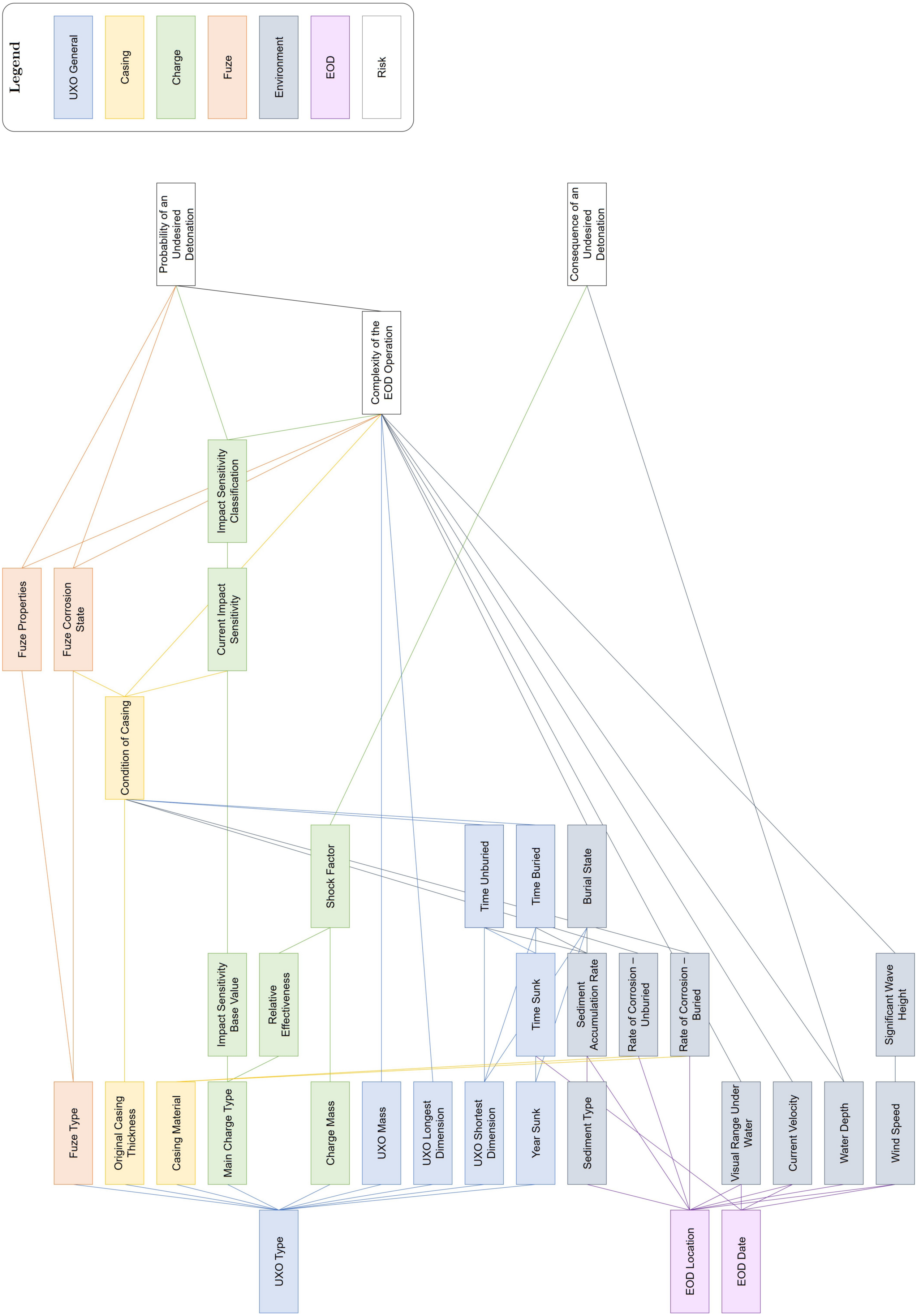

FIGURE 1 Network of UXO and environmental factors and their connection to EOD risk.

1949, which marks the reported termination of explosive ordnance dumping in Germany. Furthermore, the discussion is limited to conventional (i.e. explosive) UXO. Objects containing chemical warfare agents are not included, as this does not match the focus of the undesired event. On top of that, UXO in wrecks is ignored as it would add new layers of complexity to the issue.

3.1 | UXO risk factors

UXO is, without question, hazardous. However, the exact risk of UXO handling depends on numerous UXO properties. Information on these properties for a specific UXO type can usually be acquired from munitions databases and historic documents. It should be noted that historic documents may be incomplete or (e.g., if prepared by an opposing warring faction) erroneous. Identification of UXO in the field can be challenging (e.g., see 3.2.6), so it may be necessary to collect information on numerous UXO types in historic documents and databases.

3.1.1 | Time sunk

The duration of a UXO object‘s presence in the marine environment has an overall effect on its condition, which is why it is relevant for EOD risk assessment. The longer UXO is submerged, the longer its casing is subjected to chemical and physical corrosion (see 3.2.2). The same is true for the fuzes. Over time, the properties of the explosive material change (see 3.1.9). The degree to which this happens depends not only on the explosive compounds themselves but also on the conditions of the surrounding environment.

3.1.2 | UXO mass

The UXO mass is a factor that drives the complexity of an EOD operation. This is important because higher complexity is associated with a higher likelihood of accidents (i.e., undesired events).

Explosive ordnance is developed for many different operational purposes and is thus produced in a great variety of weights. In simple terms, it usually consists of a metal casing that is filled with explosive material, propellants, and pyrotechnics [3]. The weight of UXO mainly depends on the weight of the casing and the explosive main charge. Both are configured for the specific purpose of the object. Other parts, such as the fuze, contribute to a lesser degree.

The mass of an individual UXO object can range from less than 1 kg to several tons. One UXO type that must be expected in German waters is the British bomb D.P. 12,000-lb. Mk I, otherwise known as 'Tallboy'. One of these bombs was destroyed in situ in the river Świna near Szczecin, Poland, in 2020 [17]. The same type of bomb was also used to attack targets in Hamburg and on Heligoland [18] and thus may still be present in German waters. It has a mass of 11,885 lbs, i.e., 5,391 kg [19].

3.1.3 | Dimensions of UXO

UXO exists in many shapes and a great range of sizes. The dimensions (i.e., length, width, and height) of explosive ordnance are a consequence of its purpose and design. While some UXO objects are very small, with dimensions below 100 mm, the previously mentioned 'Tallboy' bomb has a length of 6400 mm [17]. The shape and dimensions of UXO may change over time due to corrosion, biofouling, abrasion, and, in shallow waters, wave impact [20]. Similar to a UXO object's mass, its size is a relevant factor when assessing the complexity of an EOD operation.

3.1.4 | Casing materials

The casing material of UXO determines how susceptible it is to corrosion and, thus, the condition of the object after decades under water. Casings of explosive ordnance were produced from different metals and alloys. They contain the explosive material (see 3.1.6) and the ignition chain (see 3.1.10). The casing is not the only metal part of UXO, but it is its greatest one. It is noteworthy that a study focusing on the dump site in the Eastern Scheldt (The Netherlands) calculated that metal makes up 70 % of conventional UXO's weight [3]. Steel, aluminum [21], brass (with varying factions of copper), copper, zinc [22], and different alloys [16] were used as casing materials [23].

The used casing materials were not uniform in their properties. The steel that was used for casings varied in quality [16] and carbon content [3]. After all, this study considers UXO from a period of 36 years that was manufactured using various production techniques in different countries in Europe and North America.

Some casings were not made from a single element or alloy. The piston rings of some artillery shells were made from copper [24]. Zinc and copper were used for driving bands of WWI artillery munitions [22]. Also, aluminum mines featured steel straps [25].

3.1.5 | Casing thickness and condition of casings

Similar to other UXO properties, the thickness of the casing of UXO varies greatly. The original casing thickness of the explosive ordnance when it was submerged ranged from a few millimeters to a few decimeters [16]. In one corrosion study, a casing thickness of 3 mm for bombs and of 5–7 mm for artillery shells was assumed [26]. Another study assumed casing thicknesses of 8.8–13.1 mm for artillery shells, 6 mm for bombs, and 1.5 mm for smoke grenades [27]. The 'Tallboy' had an original casing thickness ranging from 115 mm–32 mm [17].

The main mechanism affecting UXO objects' casing condition is corrosion. Details on the properties of UXO and the environmental factors that affect corrosion are given in 3.2.2. UXO exists in all conditions, ranging from fully intact to fully corroded [14]. In the period 1999–2008, a total of 1,879 UXO encounters were reported to OSPAR by its contracting parties. On 768 occasions (42 %) the reported objects were in various states of corrosion. Only in 14 instances (1 %) were the objects in good condition. For the remainder, the state was unknown or not reported [28]. For comparison, one study in Hawaii assessed 1,842 objects. Of these, 5 % were mildly corroded, 66 % were severely corroded but not breached, and the remaining 29 % were breached [29]. It is not clear why the share of severely corroded objects is so high. One explanation may be that encounters occur more often with unburied than with buried UXO, which affects the corrosion rate (see 3.2.2). UXO with a thin original casing that was recovered as early as 1953 already showed corrosion to the point that the casing was breached [30]. On the other hand, artillery shells washed ashore and found on tidal flats in Lower Saxony were reported to usually show only little corrosion in 2002 [31]. According to one report, naval mines in German waters were found in a variety of conditions, ranging from good to severely corroded. It also states that UXO that is located in the same general geographic area must not be expected to exhibit the same condition [16]. Another study reports on the condition of UXO in wrecks in Skagerrak. It confirms that UXO with thicker casings is in better condition than UXO with thinner ones. In this case, only aerial bombs were documented to be corroded to the point at which the payload interfaced with water, while artillery shells were intact [32]. The casing of UXO that is buried in the sediment or that was dumped in boxes can be expected to be in very good condition [16].

It should be mentioned that casings may also be breached by other processes than corrosion [33]. This includes abrasion from bottom sediments [34]. A breach in the casing of moored mines may also be a result of the post-war demining technique of severing the mooring and firing at the floating mine [16].

The condition of the casing is a relevant UXO factor to consider in preparation for UXO handling [11]. This is because UXO may break apart upon recovery, which may lead to the leakage of substances. [35]. The condition of the casing also affects the sensitivity of explosive materials (see 3.1.9) and the functionality of the fuze (see 3.1.11).

3.1.6 | Explosive materials in UXO

It is necessary to understand which type of explosive material is contained in UXO. The properties of these materials, such as relative effectiveness (see 3.1.8) and impact sensitivity (see 3.1.9), determine the performance and ease of detonation of the materials, which is relevant for understanding EOD risk.

One encyclopedia that was found lists 93 different explosive materials. Each of these compounds has different properties that determine how it works and, thus, how it can be used in explosive ordnance. In addition, there exist countless explosive mixtures, all with their distinct properties. The same encyclopedia lists around 180 mixtures from German production alone [36]. While not all of these are likely to be found in UXO, the number demonstrates the great variety. The other warring factions used some of the same blends but also had their own. A non-academic compilation that is available online lists 394 fillings for UXO. While this also includes CWA and other non-explosive payloads, the register underlines how many different fillings exist that may be relevant for the preparation of UXO handling [37].

In each UXO object, at least two types of explosives or explosive mixtures will be present: primary explosives and secondary explosives. Primary or initiating explosives can be brought to detonation even by small mechanical stresses or by a spark. Their purpose is to be the first element of the ignition chain, i. e., a sequence of explosive materials that detonate the main charge [38]. The ignition chain may feature a booster that has the purpose of transferring the detonation from the primary to the main charge. Whether such a booster charge exists depends on the type of UXO. The main charge contains a so-called secondary explosive [38]. It is the payload of most UXO. It is less sensitive than the primary explosive but more powerful, with a higher detonation velocity and working capacity [39].

Main charges are usually explosive mixtures, such as the German Schießwolle 39 ('gun cotton'), to name just one example. It was specifically developed for use under water [38]. This knowledge is relevant for any EOD expert who seeks to understand what type of substance they are dealing with.

3.1.7 | Mass of explosive materials

The mass of explosive material is also referred to as the net explosive quantity (NEQ). The more of this material is contained in UXO, the greater the expected consequences of a detonation. In a UXO object, this refers to all explosive substances as well as mixtures and is not limited to the main charge. The following text therefore uses the term 'charge mass' instead of NEQ when only referring to the weight of the main charge.

The amount of explosive material in UXO depends on its original purpose. Explosive material makes up 11 % of the weight of UXO at the Eastern Scheldt dump site in the Netherlands. The share of propellants is specified at 16 %. The latter group contains 70 % nitrocellulose and 15 % nitroglycerine, both of which are explosive substances [3]. Accordingly, the overall mass ratio of explosive material in the investigated UXO sample can be given as 27 %. Another claim that was found in the literature is that for projectiles, the charge mass usually contributes less than 10 % to the UXO mass [40].

In absolute terms, the charge mass in a single UXO object in the study area can be up to an approximate 5,200 lbs (2,359 kg) as is the case with the 'Tallboy' bomb [19]. One study reports that bombs can have a charge mass ranging from 5–2,000 kg [40]. Such large charges are the exception.

A study that investigated the impacts of 88 underwater detonations on the Dutch Continental Shelf in 2010 and 2011 provides information on the reported charge sizes for the detonated UXO objects. It describes charge masses ranging from 10–1,000 kg with the majority covering 125–250 kg. The dataset does not include any objects cleared by other means than detonation. It claims that most UXO found on the Dutch Continental Shelf at the time was detonated [10]. Hence, the study is not representative of other EOD methods.

3.1.8 | Relative effectiveness of explosive materials

There are numerous ways to measure the performance of an explosive material during a detonation. One of these is the relative effectiveness (RE), also referred to as the 'TNT equivalency'. Its precise definition varies in the consulted references, but they agree that it is not a physical property of the explosive material but an index factor that compares a material's performance to that of TNT. The RE of TNT is, therefore, 1.0. One review paper offers a very general definition according to which RE is the "ratio of the explosive to that of a known quantity of TNT that have the same effect" [41]. The effect is determined by the energy release of the detonation. The review paper also presents ten different methods to measure or calculate RE, some of which are supported by more detailed definitions.

Due to the multitude of methods and definitions, not even the question of whether kinetic energy, thermal energy, or both should be considered for RE has been fully clarified. Given the variety in definitions and testing methods, the values for TNT equivalency for the same explosive material can vary significantly, regularly producing errors of 20–30 % and sometimes of up to 50 % [42].

It should also be noted that RE was not developed to express the performance of explosives under water. All testing procedures described in the literature are performed in air. No research on the effect of ageing on RE was found.

When a UXO object detonates under water, several effects occur. The one that is commonly used to describe the severity of a detonation is the shock wave. The impact of this shock wave on a vessel can be quantified by a shock factor. It can also be used to quantify the impact on any other equipment or personnel in the water. The shock factor is a function of the charge mass and the relative effectiveness of the charge type. It also depends on the slant range and the depression angle between the detonating UXO object and the impacted receptor. The higher the charge mass, the relative effectiveness, or both, the higher the shock factor. The slant range is the diagonal distance between two points at different altitudes. A larger slant range leads to a lower shock factor. Finally, the shock factor increases with the depression angle [43].

3.1.9 | Sensitivity of explosive materials

Heat, friction, and impact sensitivity describe the behavior of explosive materials when thermally or mechanically stressed. These properties characterize an explosive by how much energy is required to lead to a detonation of the material. The more sensitive an explosive material is, the more likely an accidental undesired detonation is. The ageing of explosives can lead to changes – usually an increase – in their sensitivity [44]. This is true both for the primary explosive materials in the fuze [45] and the explosive materials of the main charge [46]. A decrease in sensitivity is considered possible but unlikely, as this would require the complete degradation of the energetic groups in the material [46]. Accordingly, EOD practitioners are urged to avoid putting any mechanical stress on UXO during UXO handling [47].

On the one hand, some compounds that were commonly used during both World Wars, such as TNT, are chemically very stable [48]. On the other hand, prolonged exposure of explosive materials to seawater contributes to changes in properties. Chemical reactions in materials may lead to the formation of impact- or friction-sensitive compounds. Compounds of the main charge may react with one another, with metals from the casing, or with substances that are present in the surrounding seawater or sediment [49]. Properties also change when explosive material is metabolized into other compounds by bacteria, fungi, and algae. Furthermore, environmental factors such as currents may lead to mechanical changes by grinding or washing materials out, which leads to an enlargement of the surface area [50]. Explosive mixtures change their composition when some of the included compounds are very soluble in water and others are not [51]. Finally, impact sensitivity may also increase or decrease [52] significantly when materials dry [44].

In addition to changing properties, the use of impure TNT during ordnance production may have instantaneously led to a higher impact sensitivity ex-factory than intended [46]. Tests of historical TNT and Tetryl samples showed higher impact sensitivities than what is considered acceptable when these materials are produced today [44].

It has also been reported that explosive materials can be sensitive to static electricity [40].

3.1.10 | Types of fuzes

A fuze is an element that initiates the function of explosive ordnance. There are numerous properties of fuzes that determine how likely an object is to detonate. It does so by initiating a detonator, which is filled with a sensitive primary explosive. Its purpose is to transfer energy to the main charge and initiate it. In addition, some types of explosive ordnance contain a booster between the detonator and the main charge, which is also filled with explosive material. In this case, the detonator initiates the booster, which forwards the energy to the main charge [40]. The sequence of explosive elements that detonate the main charge is referred to as an ignition chain [38].

If a fuze is present, the UXO is referred to as being fuzed. However, the presence of a fuze in a UXO object does not necessarily mean that it is armed. UXO may have been dumped, jettisoned, or used with the fuze in place but not armed. The process of arming can mean that safety features that prevent the fuze from working were removed [53]. It can also refer to the removal of safety mechanisms that separated the detonator from the main charge, which prevented the explosive chain from working [40]. The arming procedure varied among the different types of explosive ordnance. For some types of aerial bombs, the arming took place immediately before [16], during, and after they were dropped [53]. Whether this automatic arming mechanism functioned as intended depended on the drop height. Fuzes of some mines were armed with a delay [25]. In some parachute mines, arming was delayed by a clockwork mechanism [54]. If the delay mechanism seized working, the UXO object is fuzed but not armed. While dumped UXO is usually not fuzed [16], UXO that was used in combat is always fuzed and usually armed.

If they are functional, fuzes are usually triggered by an external effect, which may be mechanical, acoustic, magnetic, or electromagnetic. The sensitivity of the fuze to these effects greatly determines whether a UXO object detonates [25]. Mechanical fuzes include hydrostatic and contact fuzes. The former type was designed to be triggered by ambient water pressure at a defined depth. As the name suggests, the latter were supposed to be triggered by the physical impact of a bomb on a surface. Magnetic fuzes are triggered by changes in the ambient magnetic field that are caused by a large ferromagnetic anomaly, for example, from a passing vessel [54]. Acoustic fuzes use hydrophones to detect underwater noise that is caused by nearby vessels [16]. Depending on the functionality, fuzes may either protrude from UXO [53] or be fully integrated into it.

In opposition to a delay mechanism for the fuzing process, some fuzes have features that delay the initiation of the detonator for a few seconds. Others contain mechanisms that ensure their functionality for a long time after they were armed. Long-term functionality was assured by chemical long-delay fuzes in aerial bombs [17]. These are highly sensitive to acceleration and mechanical impact on UXO. Other options to ensure long-term functionality were retainer spring-loaded fuzes, cocked strikers, and diaphragms. These types are considered sensitive to accelerations [53]. If fuzes used a clockwork mechanism, it is possible that this mechanism failed, and thus no initiation of the primary explosive took place. Such a clockwork mechanism may restart [40].

Some UXO has special mechanisms (so-called anti-handling devices) to prevent defuzing [25]. These mechanisms use batteries, clockwork mechanisms, or operate upon mechanical impact [40].

Once triggered, a fuze can use mechanical, electrical, chemical, or heat energy to initiate the ignition chain. This means it leads to the detonation of an explosive material – the detonator [54]. In a mechanical fuze, a spike or pistol produces a mechanical impact on the primary explosive. In an electrical fuze, a spark initiates the detonation [40].

The many different types of UXO that were submerged between 1914 and 1949 were equipped with a great variety of fuzes. The following paragraphs provide an overview of the fuzes used during this period. It is non-comprehensive but describes those fuzes that are most commonly mentioned in the literature on offshore UXO.

Based on the fuze type, mines can be classified as contact mines or influence mines. Contact mines were commonly equipped with numerous chemical (Hertz) or switch horns. The former type contains a glass vial that is filled with an electrolyte liquid. When impacted by a vessel, the vial is intended to break, releasing the liquid to energize a battery [53]. In other mines, two vials contain separate liquids. When the vials break, the liquids mix and either produce an electrical charge or combustion [54]. Switch horns, on the other hand, are directly connected to a switch that is in turn connected to a battery [16]. For yet other contact mines (so-called antenna mines), a copper wire attached to a floating device extended above the mine. When in contact with the hull of a ship, the contact between two different types of metal causes a voltage change, leading to the initiation of the primary explosive [53]. Influence mines may be equipped with magnetic or acoustic [55] fuzes. Some ground mines also contain barometric fuzes that do not react to water depth but to pressure changes that can be attributed to passing vessels. In rare cases, fuzing cables were attached to mines, which allowed triggering them remotely, for example, from land. More than one type of fuze can be present in a mine [16].

Depth charges are commonly equipped with a barometric [56] or hydrostatic fuze [40]. Here, a bellows is compressed by the water pressure. This compression initiates a spring-loaded retainer spike that triggers the primary explosive. Later WWII depth charges have magnetic fuzes [53]. Others may contain impact fuzes, yet other types contain clockwork or pyrotechnic delay mechanisms [16].

Many bombs contain impact fuzes. In other cases, aerial bombs are equipped with magnetic or acoustic mechanisms [40]. Working principles to initiate the detonator may be pyrotechnical, electrical, or mechanical, including tearing wires, retainer springs, diaphragms, and cocked strikers [53]. Bombs can have numerous fuzes at different locations, for example, at the front, at the tail end, and along the side [54]. A single bomb may contain different types of fuzes [40]. Bombs intended for use against submarines were equipped with hydrostatic fuzes [54].

Fuzes in artillery shells were often armed while being fired [16]. The shells are usually equipped with impact fuzes [3] and sometimes with barometric fuzes [54]. The working principles are the same ones as for bombs [53]. Some artillery shells were equipped with time-delay fuzes [54]. Finally, torpedoes were regularly equipped with impact fuzes [53] or magnetic fuzes [16].

Given the above explanations, it is apparent that knowledge of fuze types is important for any UXO handling [11]. The different properties can be combined in various ways. These combinations determine the risk during UXO handling to a great extent.

3.1.11 | Condition of fuzes

Due to fuzes and ignition chains being submerged between 1914 and 1949, it must be expected that they are in a very different condition than when the explosive ordnance was deployed or dumped.

On the one hand, detonators may become more sensitive with time. The impact sensitivity of primary explosive materials in the detonator may change in a similar fashion as that of main-charge explosives (see 3.1.9). No measurements of increases or decreases in impact sensitivity values of submerged primary explosives were found in the literature. It is known that chemical reactions may lead to the formation of substances such as potassium chlorate and others. These are even more sensitive than the explosives that are regularly used in detonators [45]. Primary explosives in detonators may have deteriorated and leached towards the surface of the UXO object or into the fuzing mechanism. In this case, the high friction and impact sensitivity of the primary explosive can easily lead to its initiation [54]. In addition, the metal parts in fuzes are subject to corrosion. Fuzes with heavy metal parts are often strongly corroded, which makes their handling particularly challenging [16].

On the other hand, if a fuze was originally present and armed, it can be corroded to such a degree that it does not function at all [25] or not as intended, for example, because corrosion caused mechanical parts to merge [57].

It is also possible that the functionality does not change. Even ground mines from WWI were found with fuzes in very good condition [40].

In the case of some mines and torpedoes, fuzes were equipped with an energy source. If the fuze was equipped with a battery that is now empty, it cannot function as intended [58]. Magnetic [53] or acoustic [54] fuzes in influence mines are presumed to have become inoperative by today. The same is true for aerial bombs that are fitted with similar mechanisms. On the other hand, if the energy is provided by an electrolyte (such as in the Hertz horns of some contact mines), the fuze will work indefinitely as long as the wire to the detonator remains intact [45]. Lastly, it is also possible that safety mechanisms that prevented the arming of fuzes have corroded and do not perform their intended function anymore [16].

3.2 | Environmental risk factors

EOD risk depends not only on the properties of the object that shall be handled but also on the surrounding environmental conditions. Some of these affect the UXO object over many decades; others are more relevant to the execution of EOD. Especially for the latter, live data, model predictions, or at least representative values are required for a reliable risk assessment.

3.2.1 | Sedimentation and burial

Sediment is the fine-grain loose material on the sea floor [11]. There, it is vertically and horizontally distributed and is thus a determinant of the bathymetry and fundamental to the shape of the benthic environment [59].

Some properties of the sediment, such as grain sizes, may affect UXO handling. This includes the capacity of a dredger to pick up sediment, or the sediment‘s potential to reduce visibility when mobilized [47]. However, the main point of interest concerning EOD is whether an object is buried or not. If it is fully or partially buried, it needs to be uncovered during EOD. Furthermore, whether an object is buried or not influences its corrosion. It is therefore helpful to understand how much sediment accumulates at a given location. It should also be noted that explosive compounds can accumulate in the sediment [60]. The treatment of such contaminated sediments is, however, not part of the EOD procedure.

Only one-third of the Baltic Sea floor is considered to be a sediment accumulation area [61]. The remainder is considered an erosion or transport area. This includes the German part of the Baltic Sea [62]. In one study, the sediment accumulation rate in the Baltic Sea was calculated to range from 0.3–24.0 mm/year [63]. A machine learning-based algorithm that used discrete Baltic Sea sediment accumulation rate measurements predicted sediment accumulation rates ranging from 0.2–14.7 mm/year for the area to the north and east of Rügen [59, 64].

In the German North Sea, morphological changes are considerably larger than in the Baltic Sea. Coastal erosion and accumulation in shallow coastal areas with depths below 20 m can reach values way below −50.0 mm/a and above 50.0 mm, respectively [65].

High sediment mobility in an area increases the likelihood that objects are buried [25]. The higher the sediment accumulation rate, the faster an object will be buried. In addition, underwater dunes can move several meters annually and thereby bury UXO [54]. As these dunes continue their movement, objects may be exposed again. In areas with sandy sediment, a main driver of burial tends to be the erosion of the sediment around a UXO object [66]. The presence of the object on the sea floor accelerates the bottom current flow, which can increase sediment mobility. The consequence can be the development of a scour, into which the object may slowly descend. Successive sediment accumulation can easily bury an object [67]. How quickly a scour forms depends on factors such as the current velocity, wave action, sediment grain size, and the object‘s dimensions [66]. It is also possible that UXO is unburied and reburied [68]. The ratio between the density of a UXO object and the density of the sediment is another determinant of burial [69].

In addition, UXO may have penetrated the sediment immediately upon entering the sea. This is referred to as impact burial and is more prevalent in muddy sediments [66]. While also possible for dumped UXO, this mechanism is considered more relevant for ordnance that was used in combat [70]. The penetration depth depends on many factors. These are the impact velocity and angle of the munition when hitting the sea surface, the water depth and the drag coefficient of the ordnance object, and finally the shear strength, bearing strength, and density of the sediment [71]. At water depths of 2.5 m, impact burial of up to 6 m into very soft mud is considered possible [70]. Some ordnance, such as air-delivered mines, was designed not to penetrate the seabed [54].

3.2.2 | Corrosion

Corrosion significantly controls the state of the different metal parts of UXO at any given point in time. Both the casing (see 3.1.5) and the ignition chain (3.1.11) are impacted by corrosion, which starts the moment an object is submerged. As a side effect, corrosion also leads to the disappearance of markings on UXO casings, making identification more difficult [34]. The same is true if corrosion leads to a significant change in the UXO object's shape. Past research on corrosion has often addressed UXO or other containers holding CWA. The aim was usually to understand how many years after dumping and at what rate a release of the content of these UXO is to be expected. Since the casing materials used for chemical and conventional UXO were often the same [24], it is useful to review this literature.

Corrosion is affected by several environmental factors. These are the oxygenation, pH value, salinity, and temperature of seawater, as well as the current velocity. Many of these are, in turn, a function of water depth [3, 24]. Corrosion is promoted by high temperatures, oxygenation, and salinity, as well as a low pH value [72]. Water depth is also a relevant factor for tension corrosion, as it is affected by pressure [24]. On the other hand, deeper waters are less affected by weather impacts, which are considered to favor corrosion [73]. Tidal activities are relevant as well, since UXO may be exposed to air during low tide [74].

Different studies consider different environmental factors to be particularly relevant for the corrosion rate. Among them is the oxygenation of seawater, since anoxic conditions do not allow for corrosion to take place at all [24]. However, such conditions cannot be found in German waters [75]. Anoxic conditions may instead be present in sediments. This means that UXO that is buried in anoxic sediments can be expected to be in a better state than UXO that lies on the seabed [76]. The ratio of corroded to intact UXO may therefore roughly match the ratio of proud to buried objects. Based on interviews and a review of press reports, one study could confirm that UXO objects on the seabed of the Bornholm Basin were completely corroded. The state of buried objects, on the other hand, could not be confirmed [76]. Another study predicts an acceleration of corrosion when shifts between oxic and anoxic conditions occur [73].

Current velocity was identified as the main factor responsible for varying corrosion rates [27]. In addition, storm events and abrasion from bottom sediments contribute to the loss of material integrity of wrecks and, thus, also of UXO [34].

Other relevant factors impacting corrosion are inherent to the UXO casing itself. The thicker a casing, the longer it will take to corrode to a point at which the content interfaces with sea water [77]. Other factors are the material composition and carbon content of the casing and the production processes applied, especially corrosion inhibition processes [24]. Metal used for German WWII ordnance decreased in quality over the course of the war [77]. Historic research on these matters is challenging as they were poorly documented due to production confidentiality. For a precise understanding that goes beyond assumption-based modelling, attempts were made to reconstruct the chemical composition of German UXO casings from before 1946 [24]. Unlike the material used for vessels, ordnance was not specifically constructed to last in the marine environment for an extended period. Instead, it was intended that it would ultimately fail to function [34]. Numerous studies also point towards galvanic corrosion as a consequence of different metals used in the same UXO object being in contact with each other [24] or if two objects made from different materials are touching [32]. The corrosion of UXO with an aluminum casing is very limited, as aluminum corrosion stops once all of its atoms have bonded with oxygen [25]. Real-world observations show that UXO is present in all conditions, ranging from fully intact to fully corroded.

In the literature, there are numerous predictions on the amount of time required for UXO casings to corrode to the point at which an object's content leaks out. This is a point in time that is of special interest. It is the moment at which the content of a UXO object (the main charge and the ignition chain) interfaces with and is affected by seawater. It is assumed that the size of the breach in a casing grows as corrosion proceeds [33]. There is a considerable spread in the time that is expected to pass until a casing is breached. It ranges from 10–400 years [27]. None of the studies specifies that UXO is assumed to be buried in the sediment for any amount of time. The time it takes to corrode to a point at which the content of an object interfaces with seawater ranges from 25 years [24] to 50 years [78] for barrels containing CWA (i.e., not UXO). For bombs, it is given as 46 years [79]; for shells, it ranges from 69 years [79] to 300 years [80].

3.2.3 | Current velocity

Currents in general and current velocity, in particular, were already mentioned as controlling factors for sedimentation and corrosion. On top of that, currents also affect UXO handling more immediately. All of the commonly used methods for EOD (divers, remotely operated underwater vehicles (ROVs), and crawlers) are affected by currents. However, the extent of the effect differs significantly. In simple terms, divers are more negatively affected by currents than ROVs, which are usually influenced more strongly than crawlers. For ROVs and crawlers, the limitations of use that are provided by manufacturers are the information that needs to be considered for their deployment. Especially for divers, strong currents are a limitation, which may require the use of a special current shield [47]. High current velocities are a cost driver for diving operations as they limit the time windows during which work can be executed. Maximum acceptable current velocities for divers ranging from 0.25 m/s [81] to 0.5 m/s [11] were found in the literature. A non-comprehensive search for operational limits of work-class ROVs resulted in values from around 1.3 m/s [82] up to around 1.5 m/s [83].

Currents may relocate UXO or payload material. High current velocities and a low UXO mass increase the potential for mobilization [67]. Other influencing factors are the direction of currents, the shape of the UXO object, and protrusions from the UXO object. The local seabed topography also plays a role, and UXO that is mobilized may gather in depressions. Strong tidal currents in the North Sea may mobilize smaller UXO objects. It is, however, considered unlikely that larger bombs or mines will be moved over large distances by current mechanisms [54]. At dump sites, bottom currents are considered insufficient to relocate the heavy, partially buried UXO [16]. Nevertheless, the fact that UXO may not remain at one location places a certain amount of time pressure on the EOD process [20], which essentially means that the time between the completion of a technical survey and the execution of UXO handling should be minimized.

Currents are influenced by winds, waves, and tides. Since EOD takes place at the seabed, it is more important to understand the bottom currents than those at the surface. The degree to which, for example, wave action has an impact on the seabed depends on the water depth. The greater the wavelength and the shallower the water, the stronger the wave‘s interaction with the seabed [8]. Near-shore locations, which are usually less deep, are therefore considered a challenging working environment [84] (see 3.2.5).

Current velocities throughout German waters vary significantly. In the North Sea, tidal currents reach velocities of up to 1.5 m/s. They can be intensified by wind-induced currents of an additional 0.3 m/s [62]. These combined effects make the deployment of divers and ROVs impossible, and thus crawlers remain the only suitable option in areas with current velocities this high.

3.2.4 | Sea state

The sea state is another environmental property that influences the ability to perform UXO handling [11]. It is the oscillation of the sea surface and consists of wind waves and swell. The height of wind waves depends on the wind speed, wind duration, and fetch, i.e., the contact distance of the wind with the sea surface. Swell, on the other hand, are waves originating from larger-scale non-regional events, such as distant storms. The sea state can be quantified statistically by determining the significant wave height. The most common definition is that the significant wave height is the mean of the highest third of waves ($H_{1/3}$) [85].

The sea state is considered a cost and performance driver in UXO handling, as higher waves will require a larger vessel to support operations [86]. Specifications for maximum wave heights for the deployment of divers and ROVs can be found in the literature. They demonstrate the sea state‘s potential to limit offshore operations. For divers, maximum wave height values for deployment of 1 2 m [87], 1.5 m [11], and 2 m [88] were found. For ROVs, maximum launch and recovery wave heights range from 2.5–4.5 m [89].

3.2.5 | Water depth

Since UXO is located on the seabed, the water depth is a factor that should be considered during EOD. The water depth at a location can change over time, either due to long-term sedimentation or short-term tidal activities. While the tidal range in the Baltic Sea is low, it can reach over 4 m in the German North Sea. Depending on the duration of an EOD operation, it is thus possible that there is a significant change in water depth.

Similar to other environmental properties, there are operational limits for water depth for the deployment of divers and ROVs. The operational limit of divers is considered to lie in the range of 40–50 m [90]. Furthermore, dive times decrease with depth, making the use of divers less efficient in deeper waters [20]. According to the Geneva International Centre for Humanitarian Demining (GICHD), EOD diving beyond depths of 20 m requires special skills and increases technological demands [91]. For ROVs, the depth limitations are less of a concern. One review of 119 studies on ROV-based visual biota surveys found that all of the used WROVs were able to reach at least 100 m of water depth [92]. The use of robotic systems is commonly preferred over divers to mitigate human risk. However, in shallow environments, divers are by some considered the only option [93], due to the lower depth limits of most ROVs [94]. Crawlers are less affected by the wave action of the shallow water environment and thus present a reasonable alternative [94].

Numerous challenges during UXO handling are related to water depth. Lifting UXO changes the ambient pressure that it is subjected to. Reports of chemical UXO exist, according to which the inner pressure of objects led to them bursting open. Ongoing corrosion may increase the likelihood of such events [44]. It is possible that this is an issue for conventional UXO as well. Challenges do, however, not only increase with depth. Shallow waters, such as the surf zone (with depths ranging from 5–10 m), are considered to be especially challenging working environments [20]. The difficulties are mainly attributed to near-shore wave action [95].

In addition to the challenges during UXO handling, the water depth influences the potential impacts of an underwater detonation on EOD personnel and equipment. Due to the increasing pressure, deeper waters ameliorate the blast and fragmentation effects of UXO detonations at the surface [54]. In deeper waters, small amounts of explosive material are expected to cause only minor damage, even to equipment and personnel under water [23]. At more than 10 m depth, fragments are not considered a hazard for vessels at the surface [40]. Other effects, such as the shock wave and the bubble jet effect, are probably less mitigated by depth [54]. The severity of a shock wave is controlled by the distance between the detonation and the affected object. A ground mine, for example, must be close enough to its target to cause the intended damage [40]. Since greater depth also means a greater distance to a vessel, a detonation at a deeper location will lead to less shock than a detonation with otherwise identical properties in shallow waters. Consequently, shallower depths are considered more risky work environments during offshore UXO handling [40].

The water depth in Germany ranges from 0–71 m. The deepest point is located in the very north-western corner of the German EEZ in the North Sea. The deepest location in the German Baltic Sea is 47 m.

3.2.6 | Visibility and turbidity

Working underwater is impeded by the fact that visibility is limited. One factor is the decreasing amount of natural light as the water depth increases. This can be compensated for with artificial illumination. Another factor is turbidity. Turbidity is the property of a liquid "of being cloudy because a lot of small pieces of matter are held in it" [96]. It is caused by suspended matter, including sediment particles, organic matter, and microscopic organisms [97]. There are different ways of measuring turbidity. One way is to measure how a light beam of known intensity is attenuated in a liquid. Another way is to measure the degree to which light scatters in the medium [98].

Turbidity levels are higher near river estuaries and after storm events [99]. Furthermore, turbidity is often high in port areas [100]. It can also increase due to UXO handling if it leads to the mobilization of sediments. The relevance of turbidity during EOD is underlined by the fact that the use of underwater magnets is discouraged. This is, inter alia, due to them strongly dispersing sediment and rendering visual surveillance of work impossible [47].

Turbidity is inversely correlated with the ability to obtain visual information under water. High turbidity makes the EOD process more challenging since an accurate UXO identification process (e.g., with cameras) is difficult [101]. This is especially relevant when considering that this identification includes evaluating the state of a UXO object and its fuze. In addition to the collection of visual information before UXO handling is performed, lower visibility is also a challenge during their execution. It limits the ability to see what is happening to the UXO object and the EOD equipment and divers. One source indicates that high turbidity may be a limitation for divers [47]. This notion is reasonable given the higher uncertainty when less visual information is available. On the other hand, if underwater visibility is constantly poor, a diver haptically collecting information on an object may be the only option to identify it [11]. Consequently, EOD divers routinely work in dark and turbid conditions [100].

Explosive compounds accumulate in the bottom waters in the immediate vicinity of UXO, where they can reach values several orders of magnitude higher than in the surrounding waters [60]. To distinguish between UXO and non-UXO, methods for chemical sensing of explosive compounds could be used, for example, by collecting water samples with divers [101] or Niskin bottles [60]. Sediment sampling is an alternative method to determine whether an object may be UXO or not. One study found that in surface sediments, a clear gradient of explosive compounds became evident with increasing distance from a UXO object [60]. Note that water and sediment samples will not allow identifying objects but will allow discriminating UXO from non-UXO. However, it allows for drawing conclusions about the explosive materials and their properties (see 3.1.8 and 3.1.9).

Another option to obtain information for the identification of objects and UXO are acoustic cameras [102]. It is furthermore possible to equip ROVs with thrusters that blow off suspended sediment to increase visual clarity [103].

3.3 | Network of UXO and environmental risk factors

Figure 1 shows the EOD risk factor network. It features a total of 33 risk factors (21 UXO factors, 10 environmental factors, and 2 EOD factors). The UXO factors can be subdivided into the categories general (8 factors), casing (3 factors), charge (7 factors), and fuze (3 factors).

Not all factors have an immediate impact on EOD risk, as is apparent from Figure 1. Some factors influence others, which in turn determine the risk during UXO handling. Different information is available depending on whether a risk assessment is performed during the planning phase of an EOD campaign or immediately prior to the actual handling of an object. For example, when visual contact with UXO has been made, it is possible to determine the condition of the casing of an object. Earlier, during the planning, it is necessary to aim for an informed approximation of the casing condition that can be based on the year an object was sunk, the annual corrosion rate, and the burial state (which in turn depends on the sediment accumulation rate). Therefore, less immediate factors were included in the discussion in 3.1 and 3.2, as well as in Figure 1.

In addition to the UXO and environmental risk factors that were introduced above, the network contains three nodes that, in combination, express the risk of an undesired detonation. These are discussed in the following subsections, which also explain the relationship between each of the factors and EOD risk. Since some factors affect both the complexity of the EOD operation and the probability of an undesired detonation, they appear twice in the following explanations.

3.3.1 | Complexity of the EOD operation

The purpose of the node *Complexity of the EOD Operation* is to quantify how challenging the EOD operation is expected to be. While it is an output node, it also contributes to the *Probability of an Undesired Detonation.* The following risk factors contribute to the *Complexity of the EOD Operation*:

- UXO Mass: UXO with low mass can be lifted by divers, ROVs, and crawlers alike. High UXO mass means that larger and more specialized equipment is required for the execution of UXO handling.
- UXO Longest Dimension: Large objects are more challenging to handle as they have larger leverage. The larger an object, the more challenging it is to maintain an overview of it under water. Large objects have a larger surface area against which water currents can flow.
- Burial State: The deeper an object is buried, the more challenging the execution of EOD. Accessibility to the object is limited if it is partially buried. When underwater transfer or recovery needs to be executed, UXO needs to be dragged, lifted, or otherwise removed from the sediment.
- Condition of Casing: If an object's casing is in poor condition, it is more difficult to handle. It might break apart when it is lifted, or the casing may collapse when it is grabbed.
- Current Impact Sensitivity: The higher the impact sensitivity, the easier the main charge may detonate. Hence, handling has to be done with additional care to avoid accidentally impacting the main charge (e.g., by dropping the object or by hitting it with the manipulator of an ROV or crawler).
- Fuze Corrosion State: A less preserved fuze was indicated to require more careful handling by the experts during the workshop, as it is less predictable in its behavior and thus the object must be handled more carefully. If no fuze is present or if it is fully corroded, handling the object is less demanding.
- Fuze Properties: As described in 3.1.10, there are numerous features of fuzes that increase the challenge during UXO handling. The more of these features of the fuze (or fuzes) that exist, the higher the complexity of the EOD operation. If no fuze is present, other properties are irrelevant.
- Current Velocity: A higher current velocity makes the underwater work more challenging. It requires more proficient divers and stronger thrusters on ROVs.
- Significant Wave Height: Large significant wave heights have a stronger wave effect, which makes working in shallow waters more challenging. Furthermore, it increases the challenges during the deployment and return of equipment and personnel. It also directly affects the UXO if a recovery operation is executed.
- Visual Range Under Water: The lower the visual range under water, the more challenging is orientation, and the more difficult is monitoring work. It can also prevent seeing an object or nearby equipment that is required for EOD.
- Water Depth: While very shallow waters produce their own set of challenges, greater depths increase the

complexity of EOD operations since all types of equipment, and especially divers, have limitations of use.

3.3.2 | Probability of an undesired detonation

Avoiding an undesired detonation is a principle goal and purpose of offshore EOD. Therefore, it is important to understand which factors determine how likely the occurrence of such a detonation during UXO handling is. The following risk factors contribute to the *Probability of an Undesired Detonation*:

- Current Impact Sensitivity: The higher the impact sensitivity, the easier the main charge may detonate. This means that the undesired denotation does not occur due to the UXO object performing its intended purpose of detonating via the fuze but rather by a direct entry of energy into the main charge.
- Fuze Corrosion State: A deteriorated fuze is assumed by experts to trigger the ignition chain more easily and in situations in which it was not originally intended to operate, i. e., it leads to a higher probability of an undesired detonation. This issue is removed if no fuze is present or if it is fully corroded.
- Fuze Properties: As described in 3.1.10, there are numerous features of fuzes that increase the challenge during UXO handling. The more of these features of the fuze (or fuzes) that exist, the higher the probability of its initiation. If no fuze is present, other properties are irrelevant.
- Complexity of the EOD Operation: The underlying notion of this connection is that the higher the complexity, the higher the chance of accidents or errors during the UXO handling, and the higher the likelihood of the undesired event. The complexity expresses how benign or hostile the environmental conditions are and how much care needs to be applied during the execution of the UXO handling.

3.3.3 | Consequence of an undesired detonation

Avoiding an undesired detonation is the highest priority of EOD. Nevertheless, for risk management purposes, it is helpful to understand what the consequences would be if a detonation were to occur. The following risk factors contribute to the *Consequence of an Undesired Detonation*:

- Shock Factor: The shock factor, by definition, expresses how strongly a shock wave can impact equipment or personnel in the water. Therefore, the higher it is, the greater the expected consequences of an undesired event for the risk receptor.
- Water Depth: The greater the water depth, the lower the expected consequences of an undesired detonation if a risk receptor is further away from the object. If the risk receptor is located right next to the UXO, water depth is not expected to change the consequences.

4 | CONCLUSIONS

This paper presents a structured review of factors that determine EOD risk. The study focused on the risk of an undesired detonation to personnel and equipment at the EOD location. The purpose of the study was to identify the factors and understand their relationships, as well as how they contribute to EOD risk. To do so, a literature review was conducted to produce a network of risk factors. By means of an expert workshop, it was refined and improved. The result is a comprehensive EOD risk factor network consisting of 21 UXO factors, 10 environmental factors, and 2 EOD factors.

The complexity of the network demonstrates the need for a model that allows for quantifying EOD risk in a reliable and reproducible way. Currently, decision-making during EOD is very much driven by the experience and level of professionalism of the experts in charge. Based on the results of this paper, it is possible to generate a risk assessment model that mathematically expresses how the factors affect each other and how they contribute to risk. Such a tool can act as valuable support for EOD experts during their challenging decision-making process.

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DATA AVAILABILITY STATEMENT

Data may be requested via the author.

ORCID

Torsten Frey http://orcid.org/0000-0003-0834-1718

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