Progress in Disaster Science 21 (2024) 100309

Contents lists available at ScienceDirect

Progress in Disaster Science

journal homepage: www.elsevier.com/locate/pdisas

On the importance of systems thinking in ERW (explosive remnants of war) risk management

Geir P. Novik [a,b,*], Eirik B. Abrahamsen [b], Morten Sommer [b]

[a] *Norwegian Defence Research Establishment, P.O. box 25, 2027 Kjeller, Norway*
[b] *Department of Safety, Economics and Planning, Faculty of Science and Technology, University of Stavanger, P.O. box 8600, 4036 Stavanger, Norway*

ARTICLE INFO

Keywords:
Unexploded ordnance
Risk mitigation
Risk prevention
Complex risk management
Cascading risks

ABSTRACT

One of the legacies of armed conflict is unexploded ordnance and abandoned ammunition. This legacy will, in many cases, have a severe impact on society and daily life, even for years or decades after hostilities have ended. The millions of tonnes of explosive remnants that remain in nature represent a grave threat in many ways, and, if left in place, the human, societal and environmental impact could prove to be severe. Clearing the ERW represents a serious and complex risk in itself, a risk that could increase if mismanaged. Furthermore, the accumulations of munition contamination hinder and severely endanger areal development, both on land and offshore. However, vast amounts of explosives and accumulations of munitions, such as those in dumping areas and shipwrecks, are systematically neglected. An unintentional detonation at such a site could prove to have disastrous societal and environmental consequences. In the present work, it is shown that systems thinking could be used as a tool to gain better insight into the complexity of managing the risk related to explosive remnants of war, and to better prioritize resources allocated to mitigating this threat, resulting in the optimization of resource allocation and reduced societal risk.

1. Introduction

Nearly every armed conflict in modern times has left behind large numbers of explosive remnants of war (ERW). These are the thousands and sometimes millions of pieces of explosive ordnance that have been fired, dropped or otherwise delivered during the fighting but have failed to explode as intended, as well as ammunition that has been abandoned by the warring parties on the battlefield. For example, in the ongoing conflict in Ukraine, Russia's invading forces have so far left more than 40% of Ukraine's territory contaminated with landmines and unexploded ordnance [56], killing and maiming more than 1100 civilians by 2022 [22,69]. The clearing of such weapons has often taken years or even decades, depending on the scale of the challenge. According to the United Nations [67], even before the Russian invasion, Ukraine cleared 80,000 pieces of explosive debris every year, remnants of several earlier wars, and it can be safely estimated that the number of ERW generated by the ongoing conflict is growing by several millions every year.

No matter in which country they are located, or from which conflict they originate, ERW will represent a persistent problem and a deadly threat that could kill and injure large numbers of men, women and children who subsequently disturb or tamper with them [38]. In addition to the dumped ammunition, there also remain at sea thousands of sunken military and merchant vessels, containing large quantities of live ammunition, shells, mines, depth charges and other explosives, as well as some chemical warfare agents [42]. In the aftermath of war and armed conflict, it is therefore essential that unexploded ordnance (UXO) and abandoned ammunition are handled properly, to prevent accidents, illicit recovery, proliferation and misuse. However, both time and resources are limiting factors that strongly reduce the possible actions taken to secure the ammunition [45].

In most Western countries, whenever munitions or munition components are discovered by the public and reported to the authorities, specially trained personnel (in explosive ordnance disposal) are generally tasked with assessing the situation, and, if the object is considered a threat to personnel or property, it is disposed of (e.g., removed, rendered safe, detonated, etc.) [45]. Sometimes this involves evacuating a great number of people and closing venues until the object is considered safe. However, normally this only applies to those cases where clearance and remediation are urgently needed, due to acute safety risk. Measured by the number of ERW, remediation of all munitions is quite unrealistic in the near future, and the cost of such a plan is an important factor as to why this has not been seriously addressed to date [24]. These countries

---

* Corresponding author at: Konvallveien 11, 0855 Oslo, Norway.
E-mail address: Geir-Petter.Novik@ffi.no (G.P. Novik).

https://doi.org/10.1016/j.pdisas.2023.100309
Received 6 January 2023; Received in revised form 30 November 2023; Accepted 30 December 2023
Available online 2 January 2024

(e.g., United States, Canada, United Kingdom, Sweden, Norway, Germany, etc.) have, therefore, for many years, taken a passive monitoring approach to large accumulations of ERW, as in the case of known munition dumping sites and some areas heavily contaminated with UXO, such as partially destroyed ammunition stores and the thousands of sunken World War Two (WWII) vessels [47]. Whilst some of these sites are monitored for leaking constituents and their environmental effects [15], the vast majority are not. Additionally, it is frequently the case that complete archives regarding what exactly has been dumped do not even exist, nor are there any complete records on where it was dumped. Moreover, those tasked with carrying out the dumping did not always stick to the rules [58].

For many decades now, this dumped ammunition and ERW has for the most part been left undisturbed. It is clear that dumped ammunition can survive fully intact and in a pristine condition for over one hundred years, but it can also rust so thoroughly in a few decades that only non-soluble explosive filler and a few metal fragments remain [9], causing munitions' constituents to leak into the ground and water. These toxic substances from the explosives can contaminate living organisms, as well as the surrounding soil and groundwater [6,26,27,61,70], and may also enter the food chain and directly affect human health upon the consumption of contaminated food [40]. It is also clear that, as time passes, the objects will become less and less identifiable, and their chemical and technical condition will become increasingly indeterminate, thus dramatically limiting the number of potentially available risk-reducing actions. Whilst analysis of some highly explosive substances extracted from WWII ERW shows the explosives to be in generally good condition [44], there is also evidence that some explosives can become increasingly sensitive to external stress [2,50]. Some ammunition has also proved to explode spontaneously, even without human interaction [18]. Our window of opportunity is therefore diminishing rapidly. In a matter of decades, the ammunition could have become too corroded to handle; it could be further buried in sediments, making it even harder to locate, identify and retrieve, and, depending on the material, chemical and technical condition and environmental exposure, it could become unstable and unpredictable [36]. In addition, shipwrecks containing ammunition will continue to deteriorate and eventually collapse, greatly increasing both the unfeasibility and the risks of retrieving the munitions.

This passive approach towards known dumping sites, sunken vessels and areas heavily contaminated with UXO stands, however, in glaring contrast to the measures usually taken to neutralize individual ERW whenever they are discovered [3]. But, as societies' environmental, safety and security standards are improving, so their demands to politicians and governments to take preventive action to avoid unnecessary loss of life and environmental damage are increasing. The time for a passive policy of ignorance/negligence has long passed, and, for most countries, decision-makers will, at some time, be forced to make active policy choices regarding ammunition-contaminated areas (e.g. [68]). This is also confirmed by the United Nations in the "Protocol on Explosive Remnants of War to the Convention on Prohibitions or Restrictions on the Use of Certain Conventional Weapons (CCW) which may be deemed to be Excessively Injurious or to have Indiscriminate Effects (Protocol V)" [65], which states that each High Contracting Party and party to an armed conflict shall survey and assess the threat, assess and prioritize needs and practicability, mark, clear, remove and destroy ERW and "take steps to mobilise resources to carry out these activities". The protocol further states that areas affected by ERW which are posing a serious humanitarian risk "shall be accorded priority status for clearance, removal and destruction".

In this paper, we examine the prevailing practice of ERW risk management and explore how systems thinking can be used both as a tool to gain better insight into the complexity of ERW risk management and as a way of seeing the whole and interactions, enabling us to see beyond snapshots of isolated parts of the system [30]. With the use of this skill set, we hope to better understand the deep roots of complex behaviours, in order to better predict them and, ultimately, adjust their outcomes [5]. We believe that systems thinking can be beneficial when addressing the complexity and uncertainty of ERW risk and prove to be an important decision-making aid in prioritizing and conducting risk mitigation actions in the future. It is acknowledged, however, that this paper does not offer any ultimate solutions on how to handle the ERW threat but provides a guide for how to address the complexity of ERW risk and an example of how systems thinking could be utilized in the prioritization of risk mitigation actions.

Our study is a case study of the defence sector in Norway, from which we have collected data at the strategic level (developing and implementing political-military strategy), the operational level (planning and directing campaigns and major operations) and the tactical level (planning and executing tactical operations). Here, we have interviewed key actors from both the military and civilian sectors and performed a detailed systematic literature review, analysing relevant legislation, regulations and official documents applicable to conducting ERW-operations in Norway. In addition, we have used participant observation, as one of the authors has worked as a career officer in the Norwegian Armed Forces for more than 25 years, as an ammunition technical officer and explosive ordnance disposal (EOD)/improvised explosive device disposal (IEDD) operator. Furthermore, to advance the identification and assessment of potential risks related to ERW that may affect complex risk management in the present and the future, we have created an analytical framework for identifying the network structure in which ERW risk management is embedded. Based on the empirical data from the Norwegian case and a causal loop diagram (Fig. 2), we identify and visualize how certain risk-mitigating actions can cancel each other out and even enhance the overall societal risk. This type of approach accounts for the complexity and interconnectivity between and within different systems, by identifying relations and connections that have previously been considered in isolation [20]. With this analysis, we demonstrate that systems thinking could be used as a tool to gain better insight into the complexity of managing the risk related to ERW, and to better prioritize resources allocated to mitigating this threat, resulting in the optimization of resource allocation and a reduced societal risk.

2. Existing practice of ERW risk management in Norway

Based on the variety and severity of potential consequences related to energetic material such as explosives, it is evident that the risk picture related to the problem of ERW is multifaceted, with several dimensions needing to be considered. Applying a more traditional risk management model to this problem would entail significant shortcomings and sub-optimal solutions, as the traditional approach is simply too narrow [49]. When addressing the complexity and uncertainty of ERW risk, other tools are therefore needed, in order to gain better insight into its risk management.

When dealing with ERW, most countries that are affected naturally tend to prioritize objects that are regarded as an immediate and direct threat to their population (e.g. [48]). This could, for example, be munitions accidentally discovered in a former military training area or UXO exposed whilst excavating land that could have served as a battlefield or bomb target (e.g., city, industry, military, critical infrastructure, etc.) in wartime. In such cases, the risk assessment is generally straightforward: the object represents an undesired or intolerable risk, and the risk can be mitigated by (relatively) easy terms, normally by destruction, removal or by rendering it safe. There are normally established routines and contingency plans to follow, and, as this is usually a frequent occurrence, there could also be a separate budget set aside for clearing accidentally discovered ERW. The potential explosive risk and the subsequent threat to personnel and property are easily identified and will often overshadow other forms of risk associated with the object. Whenever ordnance is discovered or accidentally detonates, the focus will generally be on its potential explosive capacity and/or the potential damage a detonation could have caused. For decades, therefore, the predominant public view of risks related to ERW has been the potential explosive effect related to accidentally discovered explosive objects [47].

However, this traditional approach brings about an over-simplification of the ERW-risk picture, and our analysis suggests that the major ERW-related threats do not necessarily coincide with what are generally perceived by the public and by the decision-makers. Based on collected empirical data, it is evident that a majority of the ERW-related threats and pertinent risks are often marginalized. One possible approach in establishing a more representative risk picture would therefore be to also include and evaluate the possible risks related to ERW that are normally out of sight (e.g., dumped ammunition or accumulations of explosive objects, such as shipwrecks, etc.), in addition to the explosive objects routinely discovered by the public and disposed of by the government. Based on the collected data, it is further evident that the official (i.e., Norwegian) archives of explosive-contamination (e.g., ERW, munition dumping sites, etc.) are, for the most part, missing or incomplete. Subsequently, historical data and statistics have to investigated, in order to establish more accurate estimations of the occurrence and types of ERW present in the ground, lakes, sea, harbours, etc., as a result of war fighting and/or training. In the *threat perception iceberg,* illustrated in Fig. 1, the tip of the first iceberg represents the visual threat (i.e., ERW brought to media attention when accidentally discovered or when an unintentional detonation occurs), whilst the main body of the iceberg represents the millions of tonnes of ERW and dumped ammunition that in fact remain in nature today, unknown by (or at least unfamiliar to) the general population.

Moreover, the data demonstrated a misrepresentation of the ERW-related risks in both the media picture and among the general public. Through this analysis, a requirement to evaluate the potential risks the ERW represent to societal safety and security was identified. This would include the potential direct and indirect risk to life and health in the case of an intentional or unintentional fire or detonation, as well as the environmental, economic and political risk, illustrated by the *risk perception iceberg* in Fig. 1. In this illustration, the tip of the iceberg denotes the potential explosive risk represented by ERW, and the main body characterizes the hidden risks, often disregarded and/or overshadowed by the explosive risk.

A direct risk to life and health could occur if the object were to function, for example detonate or initiate a pyrotechnical charge that could cause a fire or an explosion which could result in injuries or casualties among the public. This could be the result of the object being subjected to sufficient force (accidental or otherwise) to cause it to function as intended (e.g., impact, friction, heat) or the ERW spontaneously exploding due to technical or chemical degradation, etc. An indirect risk could be a potential fire or explosion damaging critical infrastructure, such as a hospital, water/gas mains, etc., which in turn could represent a threat to life and health. A challenge in this regard is the common misconception that explosives in ERW become less sensitive and/or that their explosive potential reduces over time [44].

It is known that ERW contain substances that are considered poisonous to humans, and that they can pollute the soil and ground water, as well as biological life [26,27,40,61]. This means they represent not only a risk to life and health but also a broader environmental risk. As ammunition casings slowly deteriorate, harmful substances will start to leak, resulting in contamination of the surrounding land and waters. Some of these could be trapped in the sediments, whilst others could be spread by wind or water, potentially contaminating a large area. Any disturbance of the ERW (i.e., salvaging/moving) could have the potential to release substances caught in the sediments, not to mention the potential environmental consequences of an unintended accidental detonation. Even a planned and controlled detonation could, depending on the characteristics of the ammunition, result in the dispersal of harmful substances, both from the object itself and from the release of trapped substances in the sediments, as well as/or the potential for sympathetic detonations of yet undiscovered explosives and ammunition.

In addition to the explosive and environmental risk, ERW also represent a broader societal risk. In one respect, this hampers or delays development projects, as land and sea contaminated with munitions or munitions' constituents need comprehensive surveying and monitoring before any work can be done. This often demands vast resources, and the risk and economic costs will often require project plans to be altered or a project to be terminated. This could affect not only domestic and

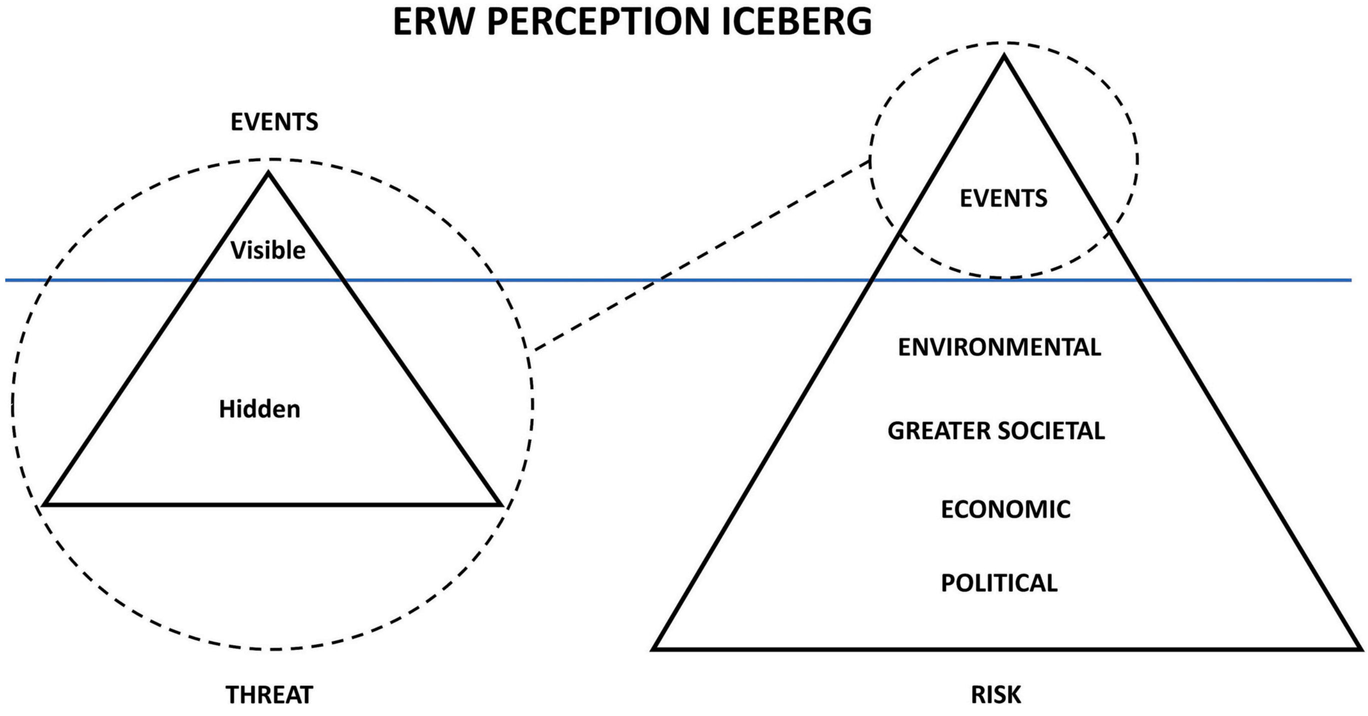

Fig. 1. ERW perception iceberg.

industrial development (e.g. [59]) but also, to a greater respect, the global effort towards green change. Examples of this could be how munitions' contamination affects projected underwater power lines / gas pipelines, the development of hydroelectric power plants, wind parks or other projects required to make the change towards more sustainable energy sources. Accidental or spontaneous detonations could also damage critical infrastructure, and ammunition contamination could also hinder the investigation, repair and rebuilding of such (e.g. [13]). Additionally, knowledge of the extent and potential of risks related to ERW could have an impact on the societal sense of safety and security. Any severe incidents involving ERW, for example accidental detonations, confirmation of harmful munitions' constituents in drinking water or food (aquaculture industry), etc., will inevitably have economic and sometimes even political consequences. The latter is especially relevant if the government's elected officials have been proved to neglect their responsibility to protect the population from the considerable risks that ERW represent.

Based on the collected empirical data, this analysis demonstrates that several ERW-related threats and pertinent risks are often marginalized or misrepresented, thus generating a potential distorted ERW risk perception.

3. The use of systems thinking to manage ERW risk

There are several challenges related to assessing and managing ERW risk that are particularly difficult to assess in the traditional technical view of risk, such as complexity, lack of knowledge, uncertainty and the elements of surprise and black swans [29]. We believe that systems thinking can be beneficial when addressing ERW risk and prove to be both an important decision-making aid in prioritizing and conducting risk mitigation actions in the future and a way of seeing the whole and interactions, enabling us to look beyond snapshots of isolated parts of the system [30]. Additionally, systems thinking can be beneficial for identifying the real roots of problems, instead of applying "end of pipe" solutions that fix only symptoms, not causes [21].

Systems thinking can be characterized as a conceptual framework for seeing the whole and interactions, rather than isolated parts of the system [30]. The basic idea is that the understanding of the *why* and *how* of something requires an understanding of the system or context. Specifically, to understand the particularities of an element or an event, there is a need first to understand the general [10]. It is a science, based on understanding connections and relations between seemingly isolated things, and can be used to discover organizational structures in systems, creating insights into the organization of causalities [21]. Through system analysis, it is possible to identify and define critical areas and/or areas of concern and to analyse them, in order to understand their components and feedback relationships. In this analysis, a mental model structure is often created, using Causal Loop Diagrams (CLD), to reflect problem areas. CLDs are also helpful for mapping out the structure of a system and its networks and revealing causalities and feedbacks within the system [21]; they are commonly used alongside systems thinking to see the interrelationships among all system components [41] and to facilitate understanding and analysis of the system under investigation [60]. An example of a CLD on the system of ERW action could therefore offer an opportunity to identify feedback effects in the system, which may point to potential future trajectories of change. Feedback effects, as visualized in the CLD, will arise when variables affect each other in a cascading manner, ultimately leading back to a previous variable, creating a feedback loop [20]. To illustrate how CLDs can be helpful in identifying causalities and feedback within a system, we developed a simplified example of the system for ERW action, as shown in Fig. 2. In this example, there are six feedback loops, with R1 referring to the reinforcing feedback loop between available EOD methodology (Options) and viable choices available to the decision-maker (Choices). In this loop, more choices will result in more options and vice versa, making it a reinforcing feedback loop, as events or behaviours created by the variables in the loop amplify each other, leading to unbounded growth or decline [20]. There are also three other reinforcing feedback loops in the example; in R2, where knowledge and (the quality of) threat assessments affect each other, in R3, where knowledge and (quality of) training affect each other in a reinforcing manner, and finally in R4 where available EOD methodology is affected by their potential negative consequences, and how this limits the feasibility of the relevant methodology. Such negative consequences would include both potential undesired collateral damage as a result of EOD action, the potential residual societal risk after action has been taken, and the coherent level

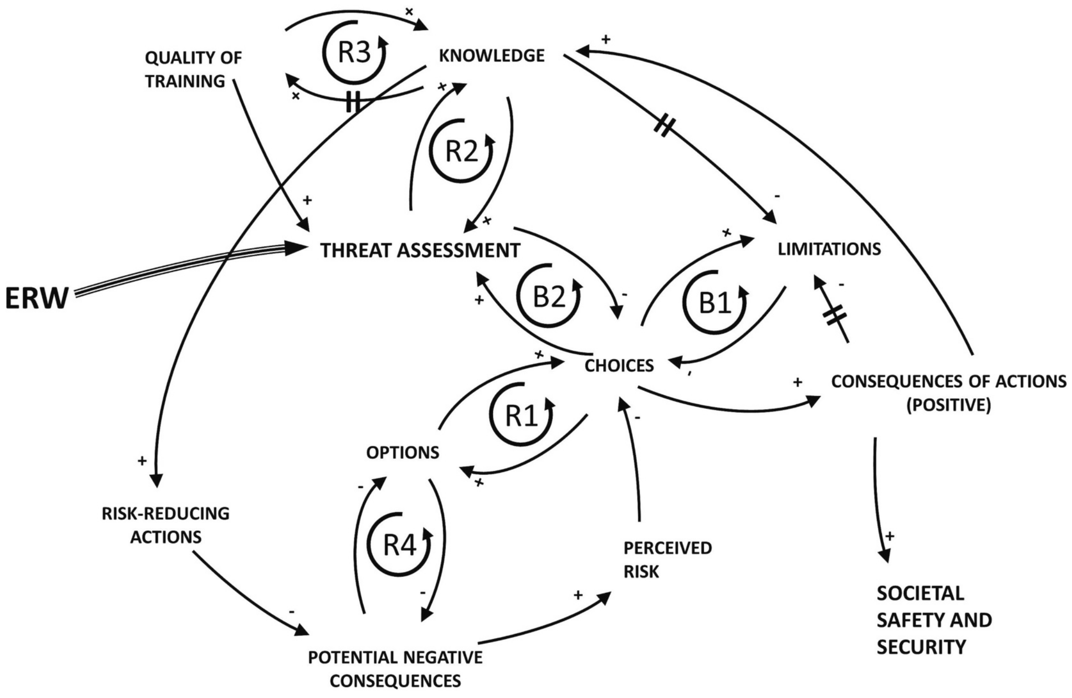

Fig. 2. Simplified CLD example, showing the system for ERW action and the potential for unrecognized influences to affect the system.

of risk and amount of resources the various EOD methodology options embody. In the visualized example, there are also two feedback loops where the variables create counteracting changes, resulting in equilibrium; B1 refers to the feedback loop of limitations and choices, showing that the more choices available to the decision-maker, the more limitations are likely to be imposed, thus reducing the number of viable choices. B2 shows how (the quality of) threat assessments affect(s) the choices available to the decision-maker and vice versa.

In this analysis, it is apparent that both the quality of training and the knowledge are critical system elements that affect the threat assessment and the possible risk-reducing actions, both having an effect on the choices available to the decision-maker and ultimately the consequences of actions. The potential consequences (positive) will result in the desired outcome of any ERW action: increased societal safety and security. It should be mentioned, however, that both positive and negative consequences of actions would equally lead to increased knowledge. Information of consequences (both negative and positive) to decision-makers at a strategic level could also prove to affect limitations, as restrictions (e.g., economic, regulatory, etc.) could be altered. In this respect, even information and/or publicity on the negative consequences of actions (e.g., undesired detonations, collateral damage, economic, political or environmental implications, etc.) could bring attention to the severity of the problem and how imposed limitations restrict the availability of EOD methodology and available choices, thus motivating a review of the limitations in the existing regulations, structure, framework, etc.

The analysis reveals a number of connections and feedback loops, only one of which will receive further scrutiny in this example. It seems that one factor that has the most profound potential impact on the system is that of limitations. Whilst some limitations can be relatively constant, such as constraints related to location, weather or time, others can be modifiable, such as regulatory, structural and economic restraints, etc. Some of the imposed limitations are also implemented for the purpose of acting as risk mitigators or safety measures in a specific area. Examples of these could be blast/frag limitations at a specific location, as high-order detonations could damage fixed critical infrastructure (e.g., gas pipelines, etc.); there could be noise regulations, as noise could be harmful to marine aquaculture or wildlife; there could be limitations in order to preserve evidence in a criminal case, etc.; or there could be limitations to preserve cultural heritage sites, etc. For such examples, it is imperative to investigate how these limitations, which are specifically designed to mitigate a defined risk, affect and interact with other parts of the system.

3.1. Potential implications

Taking a closer look at the complex network of connections reveals many counteracting forces in the system, as well as several links and potential cascading impacts that are not perhaps obvious but still highly relevant to the desired end state (i.e., increased societal safety and security). For instance, looking further into the factors that limit the selection of viable choices available to the decision-maker (limitations), it becomes clear that some, such as environmental implications, are permanent, and that others, such as framework (resources) and regulatory restrictions, may be variable. Whilst permanent limitations, by definition, are unchangeable (e.g., location, chemical, technical and environmental conditions), the variable conditions can be altered. As for framework conditions, these can be altered by regulating the level and quality of training, funding, personnel, etc. Regulatory restrictions can normally be altered by adding, removing, changing or amending relevant statutes, legislation and regulations. In many cases, the more formal regulatory restrictions are also supplemented by codes of conduct, policies and procedures that enforce further restrictions. These often also consist of several individual safety measurements put in place to reduce a specific risk.

Any change in these restrictions would have an effect on the system and, depending on its interconnection with other parts of the system, could have unintended implications for the system output. Examples of this are implications for resources and risk. Experience tells us that that the implementation of restrictions such as safety measures is not always consistent with already existing safety measures. The consequence of this can be that some safety measures may lead to the reduction of other measures that have already been implemented, resulting in the expected effects being less than intended or in no effects at all. In a worst-case scenario, they can even prove to have a negative effect [1,46]. As the resources spent on safety measures are normally limited, investments in new safety measures may also lead to reductions in investments in other safety measures planned for implementation. This is particularly significant, as it could result in less important safety measures being prioritized over more important (e.g., more cost-effective) measures in terms of effect. Additionally, continuous implementation of uncoordinated safety measures could also mean that, by the time the safety measure is implemented, the risk has already been mitigated by other means (e.g., revised procedures, training, etc.) or by other recently implemented safety measures, leaving the implementation with little or no effect, risking the needless use of resources and introducing even more restrictions/limitations. In this respect, the order in which safety measures are implemented in a complex system would also have an effect on both risk- and resource management.

One example of this is the (often unintended) reduction of the space of possibilities in which the freedom to choose work strategy is a very important means to resolve resource-demand conflicts met during performance. To determine the “space” in which the human can navigate freely, the constraints that must be respected by the actors for the work performance to be acceptable need to be determined [55]. One of these boundaries is given by the control requirements posed by the system and the other by the human resource profile, which depends on individual characteristics such as competence, mental capacity, etc. Navigation within the envelope specified by these boundaries will depend on subjective criteria for choice, such as the aim to save time and money, to spare resources, to reduce risk, to increase the cost-benefit ratio, etc. If, however, these boundaries are too stringent, the space of possibilities (i.e., the freedom to make decisions according to personal preferences) could be considerably reduced. The continuous implementation of uncoordinated restrictions (e.g., safety measures) would result in a systematic migration towards the boundary of the acceptable state of affairs and, if crossing the boundary is irreversible, an error or an accident may occur [54]. Such an error or accident could, for example, be that there is an unacceptable impact on human safety, security or the environment, or that the residual risk is considered too high. In Fig. 3, Rasmussen’s [55] model is used to illustrate the likely systematic migration towards the boundary of the acceptable state of affairs upon the continuous introduction of uncoordinated restrictions. This figure shows how the alternative acceptable work activities are shaped by the work environment, which defines the boundaries of the range of possibilities, and that stricter boundaries reduce the selection of acceptable work strategies. As presented in Fig. 2, the implementation of limitations could have a cascading effect on the system, especially if the potential undesired effects of these limitations have not been sufficiently analysed.

In addition to the potential consequences of crossing the boundary of the acceptable state of affairs, an unintended restriction of the space of possibilities could also result in a too narrow selection of available work strategies, excluding the only viable options that would result in a successful result with an acceptable risk and an optimal cost-benefit ratio. The inadvertent elimination of viable options in handling a specific ERW threat, as a result of unsynchronized restrictions, could therefore lead to not only significantly increased costs and resources but ultimately also a risk increment to both the operator and the entire society, as the probability and potential consequences of collateral damage and residual risk are likely to increase. As the resources spent on reducing the ERW threat (i.e., EOD action) are normally limited, excessive use of resources due to unsynchronized restrictions may also lead to reductions in planned EOD

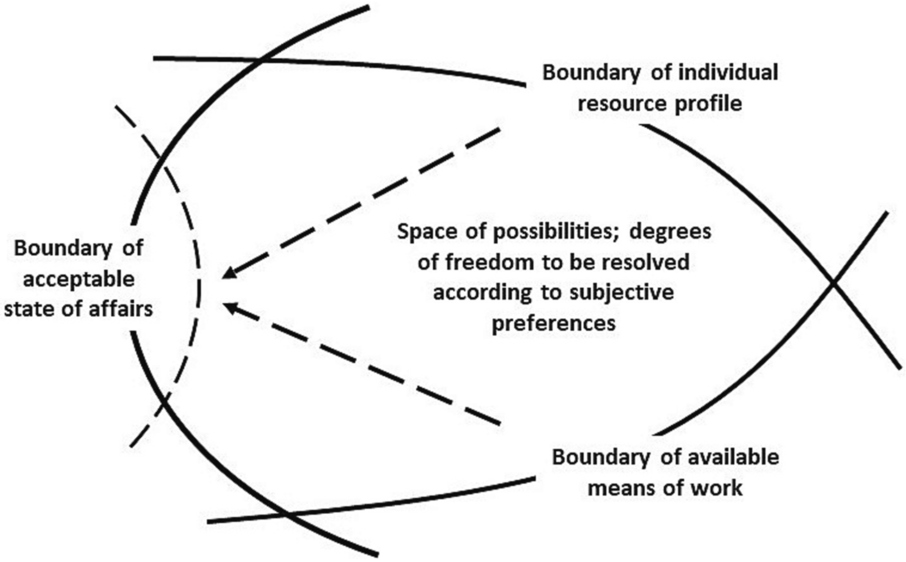

Fig. 3. Rasmussen's [55] model, identifying the "space" in which the human can navigate freely, adjusted to exemplify the migration of the gradients as a result of the continuous introduction of uncoordinated restrictions.

operations. This is particularly significant, as it could result in less resource-demanding operations being prioritized over more important operations in terms of the reduction of overall societal risk.

3.2. The implementation of uncoordinated safety measures: An example

A lack of overall understanding (systems thinking) means that one does not see the totality of the system, and that one therefore focuses exclusively on a limited area (e.g., one's area of responsibility / subject area). In an effort to improve results in this limited area, requirements are introduced (e.g., in terms of resources, efficiency, quality, etc.). Without the necessary overall understanding, such requirements may be implemented without regard for any impact within other parts of the system and for the system as a whole. Such uncoordinated requirements may limit both the variety of viable actions and the available space of possibilities in which an operator can operate freely.

In this example, we focus on EOD clearance of underwater ERW in Norwegian waters. Norway is one of the largest seafood net exporters in the world, and fish farming or aquaculture is the world's fastest growing food production technology [62]. It is therefore a concern that ERW in the ocean could affect the quality or sustainability of marine life. ERW are also considered a threat to offshore infrastructure (e.g., oil production and transportation), as well as to offshore development projects (e.g., wind parks, power lines, etc.). With their potentially devastating impact on offshore infrastructure, human safety and marine life, the munitions that still exist in Norwegian waters could have a severe impact on the environment and the world's food and energy supply. There are still hundreds of thousands of tons of ERW in Norwegian waters, making them a considerable environmental concern, as the ammunition casings deteriorate, and their harmful constituents constantly leak into the water. In many cases, the locations of the munitions or their types or quantity mean that they represent not only an environmental risk but also a threat to societal safety and security. Clearance of these objects should therefore be a prioritized task for the Norwegian Government. However, as resources are limited, a strict prioritization must be made, to determine what objects/areas should be cleared in what order. Given the current level of resources, it is evident at this stage that only a small fraction of the amount of ERW can be expected to be cleared within the next decades, and that, after a certain point in time, munitions casings have deteriorated to such a degree that they could be virtually impossible to clear.

In this context, it should be evident that the government and all involved parties must work systematically and interactively towards a common shared goal: to reduce the societal risk as much as possible, within the given framework of regulatory restraints and (limited) resources. This is especially so in the light of Norway being a High Contracting Party of Protocol V of the United Nations CCW Convention [66], which states that ERW in affected territories under its control shall be marked and cleared, removed or destroyed as soon as is feasible [65]. Consequently, all involved governmental agencies should work together on developing and maintaining both a risk assessment and a prioritization-and-action plan for how to deal with the ERW. This is, unfortunately, not the case. At this time, there is no official national policy on ERW and no coordinated systems approach for how to deal with this grave problem. Consequently, the involved governmental agencies do not have the required systems knowledge to make the optimal risk-reducing choices. This is evident not only from the lack of a national risk assessment and prioritizing plan but also when it comes to routine EOD clearance operations.

For example, underwater EOD operations may take months in the planning and can be extremely resource-demanding in both planning and execution, as (uncoordinated) environmental restrictions are imposed. Examples of such requirements could be to map and survey any vulnerable environmental values in the area and, through a comprehensive and time-consuming research and surveillance process, develop a detailed risk assessment of any potential consequences an underwater detonation and/or uncontrolled release of related hazardous components could have on these values. There could also be additional requirements, such as detailed instructions on how the operation is to be conducted, as well as what methodology is to be used, in order to reduce – as far as they know – any undesired environmental impact from the operation.

The consequence of these restrictions could very well be that some objects/locations, which are otherwise highly prioritized due to the level of assessed risk they pose to societal safety and security, are deprioritized, as, due to imposed restrictions, they become too resource-demanding compared with other, lower-prioritized objects/locations. Other consequences could be that, with an increase in the resources needed for each operation, the number of operations per year would be drastically reduced and/or only low resource-demanding objects/locations would be cleared. Such unintended consequences would mean that the reduction of societal risk is non-optimal from both a cost-benefit ratio perspective and a moral perspective. As uncoordinated restrictions have a direct effect on the prioritizing and execution of EOD operations, they will also have an impact, either directly or by implications for other parts of the system, within the area in which it was intended to mitigate the risk. In this example, the restrictions were implemented in order to reduce the environmental impact of EOD clearance operations. The consequences of the restrictions may, however, have a counteracting effect. For instance, a requirement that the object must be moved to a new location before it is rendered safe (e.g., by low-order deflagration or high-order detonation) could increase the risk of accidental detonation, thus increasing the risk, both to involved personnel and of uncontrolled pollution. Similarly, the relocation of an object could also result in the disintegration of the munitions' casings, potentially spreading harmful substances over a large area.

Another example is the requirement to use a certain disposal technique, like low-order deflagration techniques. Low-order has the potential to mitigate the acute blast effects by over 90% of those associated with conventional procedures (i.e., high-order) [52] and is often lobbied as an environmentally friendly, less damaging, less disruptive alternative to conventional detonations (e.g. [57]). Therefore, it is often suggested as the default method of munitions' disposal [53,64]. Some countries and organizations even prohibit the use of high-order detonation as a suitable technique for disposing of ERW, and others are now working towards a permanent ban [14,25]. While fairly under-communicated by lobbyists, these low-order techniques often result in an incomplete deflagration, leaving substantial quantities of the explosive material in the environment, resulting in contamination of marine life and an environmental hazard, which can ultimately even endanger human seafood consumers [39]. Whilst there is no question that, under the right circumstances, these actions may indeed achieve the intended effect (i.e., risk mitigation), a lack of coordination and systems thinking in the development and implementation of the requirements may ultimately lead to the imposed safety measures having the opposite effect. Other requirements, such as environmental mapping and surveillance, are, generally speaking, both achievable and reasonable, but, if the requirements are disproportionately high and very cost- and resource-demanding, the consequence could be that the operation is cancelled, due to limited resources, leaving the societal risk unchanged. In this case, the extent of requirements put in place to mitigate the environmental risk involving EOD action may result in the munitions not being cleared, thus leaving them to further deteriorate and pollute the surrounding environment. In this example, it is also evident that the process itself, of securing permission from the relevant environmental authority to perform underwater EOD, is both impractical and time-consuming, with unclear responsibilities, and suffers from a lack of intergovernmental coordination. An unclear and time-consuming application process, in which the responsible governmental agency also has to pay a service fee to the issuing authority, would by itself act as a demotivating factor for increasing the effectiveness and the number of ERW cleared from Norwegian waters.

As the example illustrates, there is currently no political strategy or guidelines in place regarding how to handle the thousands of tons of ERW in Norwegian waters. The relevant governmental agencies play their role as best they see fit, often acting on their own uncoordinated perception of the problem. Their immediate response, understandably, is to resolve the most visible symptoms of the problems in their relevant area of responsibility, by applying some sort of quick-fix method (i.e., implementation of safety measures) that is expected to give swift results. This sort of complex problem solving is, however, impossible to deal with in the absence of all the alternative stakeholders and without adequate system knowledge, and, as illustrated in Fig. 4, there is a tendency to become overly focused on treating the symptoms rather than dealing with the underlying cause [21]. This is not done intentionally by policymakers but, rather, stems from the absence of systems thinking and a lack of understanding of how the symptoms manifest themselves. The example further illustrates that a lack of systems thinking can lead to both an inexpedient process and the uncoordinated implementation of restrictions. The pressure for increased environmental safety reduces the space of possibilities to a point where only a strict number of choices is viable for the operator. The most severe

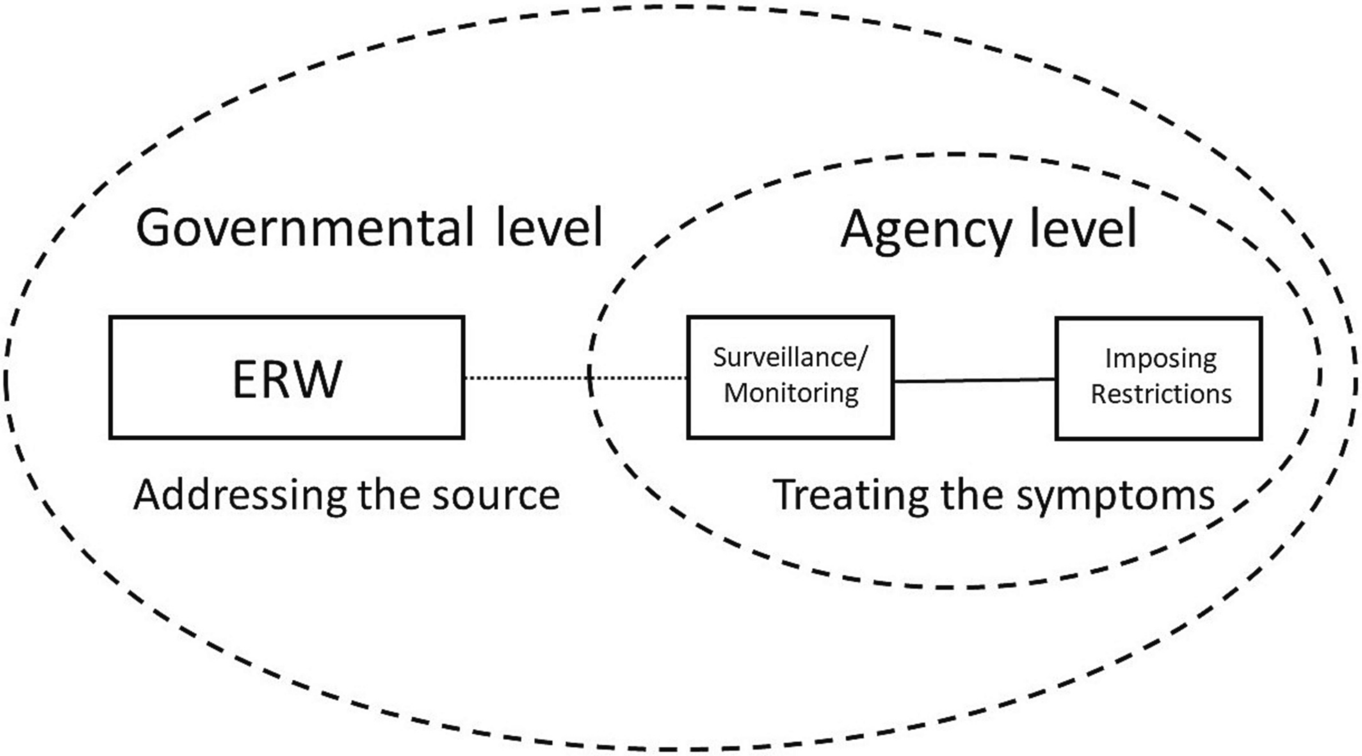

Fig. 4. In order to deal effectively with the dilemma of ERW, all relevant actors need to be included (model based on Haraldsson's [21] acid rain example).

consequence is that the only remaining viable choices could then represent an increase in the overall societal risk. Another unfortunate consequence is that any choice would normally represent a high cost- and capacity-demanding option and an inefficient use of governmental funds. In a time of limited resources, the EOD operators' choices will also be limited, and there will be pressure to implement a methodology that involves a heightened overall risk [54].

4. Discussion

Complex systems are typically characterized by high and sustained diversity of interacting components (social and institutional, environmental, and infrastructural) that produce emergent localized outcomes and include individuals or organizations that come together in an interrelated and interdependent way to shape other system components [51]. In this world of progressively complex systems, interconnections and technological advancements, each increasing the interdependence on other systems, there is a need to understand the deep roots of these complex behaviours, in order to better predict them and, ultimately, adjust their outcomes. The need for systems thinking, therefore, stretches far beyond the science and engineering disciplines, encompassing, in truth, every aspect of life [5].

The idea of systems thinking is frequently used in accident analysis, organizational theories and quality discourse [30]. As incidents, accidents and near misses most often originate in a complex combination of factors, both technical and social, systems thinking can help tease out the decisions and actions that caused a system to fail [10]. Based on this reasoning, systems thinking should, therefore, also be a necessity in risk analysis for dealing with complexity [30]. It could, therefore, be strongly argued that all people in decision-making roles should have a solid grasp of systems thinking [5].

In ERW risk management, systems thinking seems crucial. As both the risks and the risk management systems are complex, it is clear that a lack of systems thinking can result in a suboptimal use of resources and a heightened societal risk. More precisely, the lack of a systems approach results in an overcomplicated and bureaucratic intergovernmental process, unclear responsibilities and absent strategic guidance, resulting in a suboptimal use of both human and economic resources. Additionally, a lack of overall understanding can lead to an over-focus on areas that seem manageable (i.e., the symptoms) and an under-prioritization of fundamentals (i.e., the source of the symptoms). This results in short-term fixes that are adaptive at the time but could impede the development of longer-term solutions [4]. For instance, in an attempt to manage the risks at an agency level, several regulatory restrictions are put in place to govern how a specific part of the ERW risk should be managed. Isolated, such restrictions would not necessarily have any undesirable effects and could very well prove to reduce accidents and increase safety as intended; however, as a part of a complex system, they could also prove to have unintended implications for other parts of the system, possibly even reducing the overall quality and efficiency of the system. In the exemplified CLD for ERW action (Fig. 2), uncoordinated safety measures could act as a restriction (limitation) on the selection of viable choices available to the decision-maker (choices), potentially affecting the consequences of the ERW action and, ultimately, its effect on societal safety and security. The implementation of restrictions, without exploring their effect and potentially cascading impacts, would therefore have the potential for unintended negative consequences, resulting in an increased overall societal risk. One such unintended consequence could be depriving the decision-makers at the operational and tactical levels of their privilege of choice between the applicable methodologies. This will not only increase the societal risk but also significantly increase the risk for the EOD operator and deprive him/her of the means to resolve resource-demand conflicts [55], making an already difficult job much harder.

The example illustrates that complex problem solving is challenging to deal with without systems thinking and in the absence of all the alternative stakeholders. Furthermore, it also shows that adequate ERW risk assessment and management is dependent upon a conceptual framework for seeing the whole and interactions, rather than isolated parts of the system. Consequently, the implementation of systems thinking can advance the identification and assessment of potential risks related to ERW that may affect complex risk management in both the present and the future, as well as better enabling us to fulfil our requirements according to the United Nations [65] Protocol on Explosive Remnants of War.

Several existing models for systems thinking could relatively easily be implemented as is or adopted to the specifics of ERW risk, potentially providing us with a new and improved approach to safety. A well-known example of a model that could be implemented is Leveson's [32] Systems-Theoretic Accident Model and Processes (STAMP), one of the most widely used models for predictive applications in the literature [16]. STAMP is an accident causality model, based on systems theory and created as a response to the limitations of traditional causality models in the analysis of modern complex systems [32]. It covers accidents linked to both component failures and the interactions of system components [11,17,31]. This approach views the hierarchical organization, a model in which feedback loops enable a higher level (the controller) to initiate proper (re-)actions, to maintain the system in a state of equilibrium and within safety limits [37]. Through its implementation, it could be possible to better depict and review the function of safety from a systemic perspective, to increase the ability to learn from experience and particularly to deal with the complexity from the interaction among diverse system components [8].

Implementing a holistic system safety approach such as STAMP could be beneficial in developing a decision-making aid for prioritizing and conducting risk mitigation actions in the future and serve as a guide for how to address the complexity of ERW risk. As an example, STAMP is constructed from the three basic concepts: constraints, hierarchical levels of control, and process models, which, in turn, give rise to a classification of control flaws that can lead to accidents [35]. As shown in Chapter 2, some limitations, which are initially designed to mitigate a defined risk, affect and interact with other parts of the system, creating a cascading effect and effectively acting as systems constraints. As the basic concept in STAMP is not an event but a constraint, systems are viewed as hierarchical structures, in which each level imposes constraints on the activity of the level below it; constraints or lack of constraints at a higher level allow or control lower-level behaviour [12]. Safety-related constraints specify those relationships among system variables that constitute the non-hazardous or safe system states [35] – for example, the government must prevent the exposure of the public to dangerous ERW, and the EOD operator must always be able to mitigate the risks. On hierarchical levels of control, STAMP views accidents as resulting from interaction among components that violate the system safety constraints rather than as the result of an initiating event in a series of events leading to a loss. A key factor is therefore that the control processes enforcing these constraints must limit system behaviour to the safe changes and adaptations implied by the constraints. The third basic concept in STAMP is that of process models and implies that any controller must contain a model of the system being controlled. According to Leveson et al. [35], accidents, and particularly system accidents, frequently result from inconsistencies between the model of the process used by the controllers and the actual process state, for example, the decision-makers do not have sufficient situational awareness and make decisions that could seriously increase the risks, or that multiple controllers and decision-makers make uncoordinated decisions or wrongfully assume the other is carrying out the required control actions.

As STAMP can be viewed as more of a model or set of assumptions about how accidents occur than an analysis method, fully implementing STAMP into ERW risk management would require new analysis methods constructed using STAMP as a basis. One widely used hazard analysis technique, based on STAMP, is STPA (System Theoretic Process Analysis), a proactive analysis method that analyses the potential cause of accidents during development, so that hazards can be eliminated or controlled [23,34]. A basic STPA analysis would generally consist of four fundamental steps [63], the first being defining the purpose of the analysis: potential losses, safety goals, system and system boundaries. If applied to ERW risk management, the first step would then be to determine the main focus of the system: is it on preventing loss of human life or will it be applied more broadly to security, environment, efficiency and other system properties? The second step would be to build a model of the system that captures functional relationships and interactions by modelling the system as a set of feedback control loops, an example of which is shown in Fig. 2. This model, otherwise called a control structure, usually begins at a very abstract level and is iteratively refined to capture more detail about the system. The third step would then be to analyse control actions in the control structure, to examine how they could lead to the losses defined in the first step. Any unsafe control actions identified will then be used to create functional requirements and constraints for the system, for example, if the main focus of the EOD operation is to prevent the loss of life and if it is identified that one of the control actions in the control structure (i.e., the B1 feedback loop in Fig. 2) could contribute to such a loss. As shown in Chapter 2, this includes uncoordinated safety measures that unintentionally act as restrictions on the selection of viable choices available to the decision-maker, potentially affecting the consequences of the ERW action and, ultimately, its effect on societal safety and security. There are several ways in which a control action can be unsafe, including if not providing the control action leads to a hazard, if providing the control action leads to a hazard or if providing a potentially safe control action – but too early, too late or in the wrong order [63]. The fourth step in an STPA analysis in ERW risk management would be to identify the reasons why unsafe control might occur in the system, for example, how incorrect feedback, inadequate requirements and other factors could cause unsafe control actions and ultimately lead to losses, and how safe control actions might be provided but not followed or executed properly, leading to a loss. Once the scenarios are identified, they can be used to create additional requirements or to identify mitigations, etc. An example of the steps in a basic STPA analysis that could be applied in ERW risk management is shown in Fig. 5.

In ERW risk management, STPA can also be employed to identify the leading indicators used to identify the potential for an accident before it occurs, so measures can be taken to prevent it. These indicators are based on the assumption that major accidents are not due to a unique set of random, proximal events. Instead, accidents result from “The migration of an organization to a state of increasing risk over time as safeguards and controls are relaxed due to conflicting goals and tradeoffs and reduced perceptions of risk leading to more risky behavior” ([33], p. 101). This implies that major accidents develop over time and, therefore, the possibility exists to intervene. A leading indicator would be a signal that points towards the necessity of an intervention. For ERW risk management, these indicators could be beneficial in identifying causes of accidents that may arise in technical system development, in operations and in management. Some of these hazards could previously not have been identified due to inadequacies in the hazard analysis process or in how it is performed or because hazards are identified but their probability of occurrence is judged to be negligible, and thus it is believed that they will not occur [7]. Examples of the latter are seen regularly in ERW risk management, particularly relating to the vast quantity of unplanned explosions in stored or abandoned munitions, in unexploded ordnance and at ammunition dumping sites (e.g. [18,19,28]). Moreover, these indicators can help identify controls that are assumed to be operational but that do not actually exist, are not used or are not as effective as presumed. This includes controls that have changed over time and now violate the assumptions underlying their original design [33]. The indicators could further help identify flaws in the safety management system design. For example, the system could be effective but, for a number of possible reasons, does not operate according to its design and as it is assumed to operate. Such reasons could include the degradation of safety culture over time, a negative change in the safety culture (i.e., by implementing safety measures with unintended negative effects) or the behaviour of those making safety-related decisions being influenced by competitive, financial or other pressures [33].

As illustrated here, STAMP incorporates principles of system design and operation, which promote adequate control actions that enforce safety constraints, and can be a beneficial model to foster evaluation of a complex system holistically and uncover useful levers for the elimination of future loss potential [43]. By implementing this or other appropriate models for system thinking and system analysis in ERW risk management, it will be possible to identify and define critical areas or areas of concern, and to analyse them to better understand their components and feedback relationships. This approach could not only offer an opportunity to identify the potential for an accident before it occurs but could also be used as a tool to gain better insights into the

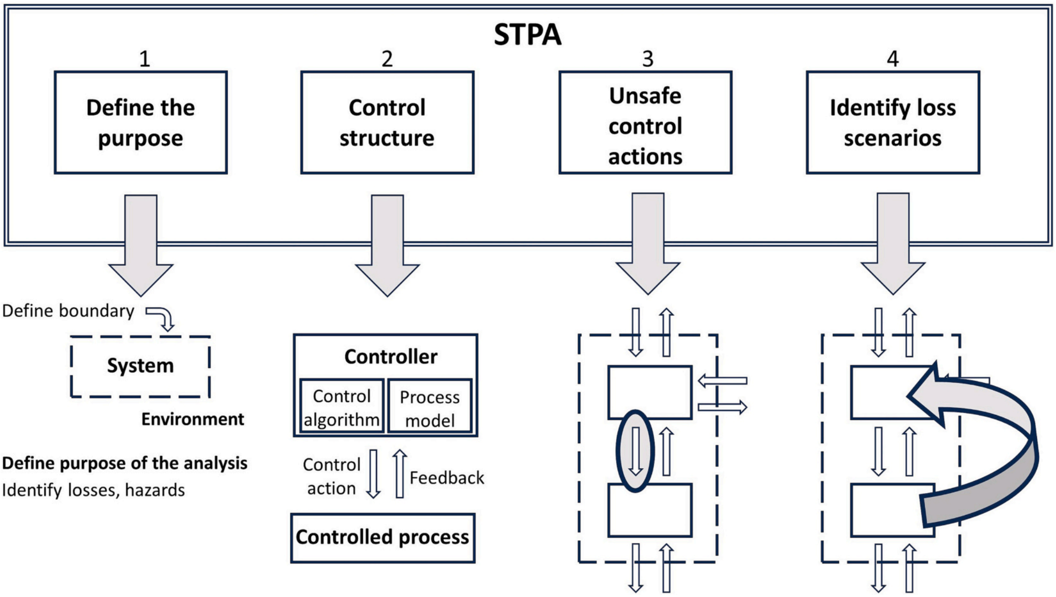

Fig. 5. The basic steps for implementing STPA analysis in ERW risk management (model based on Thomas [63]).

complexity of managing the risks related to ERW and to better prioritize resources allocated to mitigating this threat, resulting in improved economic efficiency and a more favourable cost-to-benefit ratio [45].

5. Concluding remarks

In this paper, we point out the importance of having a systems approach in ERW risk management, especially when introducing factors that could act as limitations in the system, such as regulations, procedures and instructions.

As both the risks and the ERW risk management systems are complex phenomena with multiple attributes, it is evident that a lack of systems thinking can result in a suboptimal use of resources and a heightened societal risk. More precisely, the lack of a systems approach can result in an excessively complicated and bureaucratic intergovernmental process, unclear responsibilities and absent strategic guidance, resulting in the suboptimal use of both human and economic resources. Additionally, a lack of overall understanding can lead to an excessive focus on areas that seem manageable (i.e., the symptoms) and an insufficient prioritization of the fundamentals (i.e., the source of the symptoms), resulting in short-term solutions that are adaptive at the time but that could impede the development of longer-term solutions. It can therefore be concluded that the current approach to ERW risk mitigation is forcing actors to focus merely on the symptoms, which is diverting them from confronting the fundamental issues underpinning the problem.

By implementing models for systems thinking principles and system analysis in ERW risk management (e.g., STAMP), it will be possible to analyse and improve the existing management system or to create a new one with its assistance, if required. Based on the examples and the ensuing discussion, demonstrating that adequate ERW risk assessment and management is dependent upon a conceptual framework for viewing the whole and interactions rather than merely isolated parts of the system, it has been shown that system analysis can be used to better depict and review safety from a systemic perspective. This would increase our ability to learn from experience and particularly to deal with the complexity from the interaction among diverse system components, providing insight into how to make improvements in ERW risk management.

Consequently, systems thinking should be a necessity in ERW risk analysis and risk management, as well as an integral part of the continuous evaluation of existing and proposed new safety measures. It is our opinion that the adoption of a system-theoretic approach to safety would be an effective way to integrate safety in a complex system such as ERW risk management, and that the implementation of relevant models for systems thinking and system analysis would generate a more optimal use of limited resources, as well as a decreased overall societal risk.

Funding

This research is funded by the Norwegian Defence Research Establishment. The funding source had no involvement in the research and/or preparation of this article.

CRediT authorship contribution statement

Geir P. Novik: Conceptualization, Writing – original draft, Writing – review & editing. **Eirik B. Abrahamsen:** Conceptualization, Supervision, Validation, Writing – review & editing. **Morten Sommer:** Conceptualization, Supervision, Validation, Writing – review & editing.

Declaration of competing interest

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

Data availability

No data was used for the research described in the article.

References

[1] Abrahamsen EB, Moharamzadeh A, Abrahamsen HB, Asche F, Heide B, Milazzo MF. Are too many safety measures crowding each other out? Reliab. Eng. Syst. Saf. 2018;174:108–13. https://doi.org/10.1016/j.ress.2018.02.011.

[2] Albright R. Cleanup of chemical and explosive munitions: Location, identification and environmental remediation. 2nd ed. William Andrew; 2012.

[3] Alexander DE. The strange case of the Richard Montgomery: on the evolution of intractable risk. Saf. Sci. 2019;120(December 2019):575–82. https://doi.org/10.1016/j.ssci.2019.08.010.

[4] Amalberti R, Vincent C. Managing risk in hazardous conditions: improvisation is not enough. BMJ Qual. Saf. 2019;29(1). https://doi.org/10.1136/bmjqs-2019-009443.

[5] Arnold RD, Wade JP. A definition of systems thinking: a systems approach. Proc. Comput. Sci. 2015;44:669–78. https://doi.org/10.1016/j.procs.2015.03.050.

[6] ATSDR. Toxicological Profile for 2,4,6-trinitrotoluene. https://wwwn.cdc.gov/TSP/ToxProfiles/ToxProfiles.aspx?id=677&tid=125; 1995.

[7] Aven T. Risk, surprises and black swans. In: Fundamental ideas and concepts in risk assessment and risk management. Routledge; 2014.

[8] Banda OAV, Goerlandt F. A STAMP-based approach for designing maritime safety management systems. Saf. Sci. 2018;109(November 2018):109–29. https://doi.org/10.1016/j.ssci.2018.05.003.

[9] Barton JV, Pollack SB. Assessment of lethal chemical and conventional munitions in the Nation's waters. Prepared for: CDC/NCEH; 2017. https://truthout.org/wp-content/uploads/legacy/documents/2017_1002/CDC_report.pdf.

[10] Bennett S. Systems-thinking for Safety. Peter Lang Ltd.; 2019.

[11] Chaal M, Banda OAV, Glomsrud JA, Basnet S, Hirdaris S, Kujala P. A framework to model the STPA hierarchical control structure of an autonomous ship. Saf. Sci. 2020;132(December 2020). https://doi.org/10.1016/j.ssci.2020.104939.

[12] Checkland P. Systems thinking, systems practice. John Wiley & Sons; 1981.

[13] Coogan SW. Ammunition fra Anden Verdenskrig besværliggør efterforskning af Nord stream-eksplosion [ammunition from the second world war complicates the investigation of the "Nordic stream" explosion]. DR; 2022. https://www.dr.dk/nyheder/seneste/morten-boedskov-ammunition-fra-anden-verdenskrig-besvaerliggoer-efterforskning-af.

[14] Cottrell L, Dupuy K. Alternatives to open burning and open detonation: the disparity between HMA and commercial best practices. J. Convent. Weap. Destruct. 2021;21(1). https://commons.lib.jmu.edu/cisr-journal/vol25/iss1/22.

[15] Craig HD, Taylor S. Framework for evaluating the fate, transport, and risks from conventional munitions compounds in underwater environments. Mar. Technol. Soc. J. 2011;45(6):35–46. https://doi.org/10.4031/MTSJ.45.6.10.

[16] Düzgün HS, Leveson N. Analysis of soma mine disaster using causal analysis based on systems theory (CAST). Saf. Sci. 2018;110(December 2018):37–57. https://doi.org/10.1016/j.ssci.2018.07.028.

[17] Fleming CH, Spencer M, Thomas J, Leveson N, Wilkinson C. Safety assurance in NextGen and complex transportation systems. Saf. Sci. 2013;55(June 2013):173–87. https://doi.org/10.1016/j.ssci.2012.12.005.

[18] Ford G, Ottemöller L, Bapite B. Analysis of Explosions in the BGS Seismic Database in the Area of Beaufort's Dyke, 1992-2004 (British Geological Survey Commissioned Report, CR/05/064 Issue). https://webarchive.nationalarchives.gov.uk/20121203195642/http://www.mod.uk/NR/rdonlyres/712B6133-E353-4030-9DD0-F677DC3B6F38/0/bgs_beauforts.pdf; 2005.

[19] Gonzalez JC. WWII bomb self-detonates in German field, leaves crater. Deutsche Welle; 2019 June. https://www.dw.com/en/wwii-bomb-self-detonates-in-german-field-leaves-crater/a-49331435.

[20] Groundstroem F, Juhola S. Using systems thinking and causal loop diagrams to identify cascading climate change impacts on bioenergy supply systems. Mitig. Adapt. Strateg. Glob. Chang. 2021;26(29):1–48. https://doi.org/10.1007/s11027-021-09967-0.

[21] Haraldsson HV. Introduction to system thinking and casual loop diagrams reports in ecology and environmental engineering. Issue, https://www.researchgate.net/publication/258261003_Introduction_to_system_thinking_and_causal_loop_diagrams; 2004.

[22] IMPACT. Ukrainian crisis, situational analysis. UN OCHA; 2023. Retrieved from, https://reliefweb.int/report/ukraine/ukrainian-crisis-situational-analysis-27-jan-2023.

[23] Jung S, Heo Y, Yoo J. A formal approach to support the identification of unsafe control actions of STPA for nuclear protection systems. Nucl. Eng. Technol. 2022;54(5):1635–43. https://doi.org/10.1016/j.net.2021.10.033.

[24] Kampmeier M, Lee EVD, Wichert U, Greinert J. Exploration of the munition dumpsite Kolberger Heide in Kiel Bay, Germany: example for a standardised hydroacoustic and optic monitoring approach. Cont. Shelf Res. 2020;198(104108). https://doi.org/10.1016/j.csr.2020.104108.

[25] Koschinski S, Kock K-H. Underwater unexploded ordnance – methods for a cetacean-friendly removal of explosives as alternatives to blasting. https://www.ascobans.org/sites/default/files/document/AC22_Inf_4.6.e_Ordnance_Removal.pdf; 2015.

[26] Koske D, Goldenstein NI, Kammann U. Nitroaromatic compounds damage the DNA of zebrafish embryos (Danio rerio). Aquat. Toxicol. 2019;217(105345). https://doi.org/10.1016/j.aquatox.2019.105345.

[27] Koske D, Goldenstein NI, Rosenberger T, Machulik U, Hanel R, Kammann U. Dumped munitions: new insights into the metabolization of 2,4,6-trinitrotoluene in Baltic flatfish. Mar. Environ. Res. 2020;160(104992). https://doi.org/10.1016/j.marenvres.2020.104992.

[28] Kråkenes C. Lynnedslag traff bombe fra andre verdenskrig [lightning struck in WW2 bomb]. NRK [Norwegian]; 2019. https://www.nrk.no/tromsogfinnmark/lynnedslag-traff-bombe-fra-andre-verdenskrig-1.14672572.

[29] Kringen J. Regulering og tilsyn som kunnskapsområde og forskningstema. In: Lindøe PH, Kringen J, Braut GS, editors. Risiko og tilsyn [risk and supervision]. 2nd ed. Universitetsforlaget; 2015.

[30] Langdalen H, Abrahamsen EB, Selvik JT. On the importance of systems thinking when using the ALARP principle for risk management. Reliab. Eng. Syst. Saf. 2020; 204(107222). https://doi.org/10.1016/j.ress.2020.107222.

[31] Leveson N. A systems approach to risk management through leading safety indicators. Saf. Sci. 2015;136(April 2015):17–34. https://doi.org/10.1016/j.ress.2014.10.008.

[32] Leveson NG. Engineering a safer world; Systems thinking applied to safety. The MIT Press; 2011.

[33] Leveson NG. Identifying leading indicators using STPA. In: Leveson NG, Thomas JP, editors. STPA handbook. Massachusetts Institute of Technology; 2018. http://psas.scripts.mit.edu/home/get_file.php?name=STPA_handbook.pdf.

[34] Leveson NG. Introduction. In: Leveson NG, Thomas JP, editors. STPA handbook. Massachusetts Institute of Technology; 2018. http://psas.scripts.mit.edu/home/get_file.php?name=STPA_handbook.pdf.

[35] Leveson NG, Daouk M, Dulac N, Marais K. Applying STAMP in accident analysis. M. I. o. T. E. S. Division; 2003. http://hdl.handle.net/1721.1/102905.

[36] Long TP. Introduction to Sea Dumped Munitions and Hazardous Wrecks. https://www.drpaulwcollins.com/wp-content/uploads/2019/04/Introduction-to-Sea-Dumped-Munitions-and-Hazardous-Wrecks-Terrance-P.-Long.pdf; 2005.

[37] Lunde A, Njå O. A systems thinking approach to safety in Norwegian avalanche rescue operations. Saf. Sci. 2021;144(December 2021). https://doi.org/10.1016/j.ssci.2021.105466.

[38] Maresca L. A new protocol on explosive remnants of war: the history and negotiation of protocol V to the 1980 convention on certain conventional weapons. Intern. Rev. Red Cross 2004;86(856):815–35. https://doi.org/10.1017/S1560775500180472.

[39] Maser E, Strehse JS. "Don't Blast": blast-in-place (BiP) operations of dumped world war munitions in the oceans significantly increase hazards to the environment and the human seafood consumer. Arch. Toxicol. 2020;94:1941–53. https://doi.org/10.1007/s00204-020-02743-0.

[40] Maser E, Strehse JS. Can seafood from marine sites of dumped world war relicts be eaten? Arch. Toxicol. 2021. https://doi.org/10.1007/s00204-021-03045-9.

[41] Monat JP, Gannon TF. What is systems thinking? A review of selected literature plus recommendations. Am. J. Syst. Sci. 2015;4:11–26. https://doi.org/10.5923/j.ajss.20150401.02.

[42] Monfils R. The global risk of marine pollution from WWII shipwrecks: Examples from the seven seas. International Oil Spill Conference. 2005.

[43] Nelson PS. A STAMP analysis of the LEX Comair 5191 accident Lund University. http://sunnyday.mit.edu/papers/nelson-thesis.pdf; 2008.

[44] Novik GP. Analysis of samples of high explosives extracted from explosive remnants of war. Sci. Total Environ. 2022;842(156864). https://doi.org/10.1016/j.scitotenv.2022.156864.

[45] Novik GP. Complex risk management in explosive-contaminated areas: explosive remnants of war (publication number UiS no. 701) University of Stavanger. Stavanger; 2023. https://uis.brage.unit.no/uis-xmlui/handle/11250/3068485.

[46] Novik GP. When a safety measure becomes a risk accelerant: removing the option to blast-in-place when clearing explosive remnants of war. J. Convent. Weap. Destruct. 2023;27(1). https://commons.lib.jmu.edu/cisr-journal/vol27/iss1/5.

[47] Novik GP, Sommer M, Abrahamsen EB. A risk-increasing safety strategy? Evaluating the traditional risk mitigating strategy in dealing with dumped ammunition and explosive remnants of war. J. Mil. Strateg. Stud. 2022;22(1). https://jmss.org/article/view/72969/56178.

[48] Novik GP, Abrahamsen EB, Sommer M. Improving the decision-making basis by strengthening the risk assessments of unexploded ordnance and explosive remnants of war. Saf. Sci. 2023;160(106065). https://doi.org/10.1016/j.ssci.2023.106065.

[49] Olsen OE, Juhl KV, Engen OA, Lindøe PH. Standardization and risk governance: A multi-disciplinary approach. 1st ed.vol. 1. Routledge; 2020. https://doi.org/10.4324/9780429290817.

[50] OSPAR Commission. Assessment of the impact of dumped conventional and chemical munitions (update 2009). O. Commission; 2009. https://www.ospar.org/documents?v=7110.

[51] Patel SS, McCaul B, Cáceres G, Peters LER, Patel RB, Clark-Ginsberg A. Delivering the promise of the Sendai framework for disaster risk reduction in fragile and conflict-affected contexts (FCAC): a case study of the NGO GOAL's response to the Syria conflict. Progr. Disast. Sci. 2021;10(100172). https://doi.org/10.1016/j.pdisas.2021.100172.

[52] Pedersen A, Nokes J, Wardlaw D. Low-Order, Underwater Detonation. https://apps.dtic.mil/sti/citations/ADA603983; 2002.

[53] Randall I. Joanna Lumley makes an explosive point! Actress sets off detonation in a quarry to show how blowing up unexploded WW2 bombs at sea is deafening whales and dolphins. Mail Online, https://www.dailymail.co.uk/sciencetech/article-10399471/Joanna-Lumley-sets-detonation-blowing-WW2-bombs-sea-deafens-marine-life.html; 2022.

[54] Rasmussen J. Risk management in a dynamic society: a modelling problem. Saf. Sci. 1997;27(2–3):183–213. https://doi.org/10.1016/S0925-7535(97)00052-0.

[55] Rasmussen J. The role of error in organizing behaviour. BMJ Qual. Saf. 2003;12: 377–83. https://doi.org/10.1136/qhc.12.5.377.

[56] RFE/RL. (2023). Ukraine has largest minefield in the world, prime minister says. Radio Free Europe/Radio Liberty https://www.rferl.org/a/ukraine-largest-minefield-shmyhal/32214163.html#:~:text=The%20mined%20area%2C%20according%20to,main%20industries%2C%22%20he%20said.

[57] Robinson SP, Wang L, Cheong S-H, Lepper PA, Marubini F, Hartley JP. Underwater acoustic characterisation of unexploded ordnance disposal using deflagration. Mar. Pollut. Bull. 2020;160(111646). https://doi.org/10.1016/j.marpolbul.2020.111646.

[58] Ross D. Government won't remove thousands of tons of potentially toxic chemical weapons dumped off US coast. Truthout 2017. https://truthout.org/articles/government-won-t-remove-thousands-of-tons-of-potentially-toxic-chemical-weapons-dumped-off-us-coasts/.

[59] Sabbagh D. Bombs dumped in Irish Sea make bridge plan 'too dangerous'. The Guardian; 2020. https://www.theguardian.com/politics/2020/feb/14/bombs-dumped-in-irish-sea-make-bridge-plan-too-dangerous.

[60] Sanches-Pereira A, Gómez MF. The dynamics of the Swedish biofuel system toward a vehicle fleet independent of fossil fuels. J. Clean. Prod. 2015;96. https://doi.org/10.1016/j.jclepro.2014.03.019.

[61] Schuster R, Strehse JS, Ahvo A, Turja R, Maser E, Bickmeyer U, et al. Exposure to dissolved TNT causes multilevel biological effects in Baltic mussels (Mytilus spp.). Mar. Environ. Res. 2021;167(105264). https://doi.org/10.1016/j.marenvres.2021.105264.

[62] Smith M, Roheim C, Crowder L, Halpern B, Turnipseed M, Anderson J, et al. Sustainability and global seafood. Science 2010;327:784–6. https://doi.org/10.1126/science.1185345.

[63] Thomas JP. How to do a basic STPA analysis. In: Leveson NG, Thomas JP, editors. STPA Handbook. Massachusetts Institute of Technology; 2018. http://psas.scripts.mit.edu/home/get_file.php?name=STPA_handbook.pdf.

[64] UK Government. Policy paper - Marine environment: unexploded ordnance clearance joint interim position statement. https://www.gov.uk/government/publications/marine-environment-unexploded-ordnance-clearance-joint-interim-position-statement/marine-environment-unexploded-ordnance-clearance-joint-interim-position-statement; 2022.

[65] United Nations. Protocol on explosive remnants of war (CCW/MSP/2003/2). Issue, https://documents-dds-ny.un.org/doc/UNDOC/GEN/G03/653/61/PDF/G0365361.pdf?OpenElement; 2003.

[66] United Nations. High contracting parties and signatories CCW. https://www.un.org/disarmament/the-convention-on-certain-conventional-weapons/high-contracting-parties-and-signatories-ccw/; 2022.

[67] United Nations. Making Ukraine safe again: Cleaning up one of the world's most mine-contaminated countries. UN Development Programme; 2023. https://reliefweb.int/report/ukraine/making-ukraine-safe-again-cleaning-one-worlds-most-mine-contaminated-countries.

[68] United States General Accounting Office. Military munitions - DOD needs to develop a comprehensive approach for cleaning up contaminated sites, GAO-04-147. U. S. G. A; 2003. Office, https://www.gao.gov/assets/gao-04-147.pdf.

[69] US CSCE. Demining Ukraine. US Commission on Security and Cooperation in Europe; 2022. https://www.csce.gov/international-impact/events/demining-ukraine.

[70] Yinon J. Toxicity and metabolism of explosives. CRC Press; 1990.