A Digital Twin for Training Marine Pollution Control

Maria Dias
University of Coimbra, CISUC, DEI
Coimbra, Portugal *mddias@student.dei.uc.pt*

João Barata
University of Coimbra, CISUC, DEI
Coimbra, Portugal *barata@dei.uc.pt*

Licínio Roque
University of Coimbra, CISUC, DEI
Coimbra, Portugal *lir@dei.uc.pt*

Abstract

This paper presents a Digital Twin to prepare an international response to marine pollution events. This research is conducted by a multidisciplinary team of information systems and marine pollution experts to create a digital environment suitable to represent near-real-time pollution events, assisting the command structure and combat teams in improving performance and knowledge of standard protocols. The reported results were obtained in the first year of the project and included (1) the Digital Twin architecture, (2) the simulation of the natural conditions, and (3) the prototype of the performance evaluation dashboard. Our findings suggest that current simulation systems help inform decisions but are insufficient to prepare complex scenarios requiring coordination between multiple agents operating in extreme conditions. Digital Twins can help in preparing procedures and evaluating performance in digital representations. This study contributes to a recent Digital Twin literature trend that aims to create digital replicas of comprehensive sociotechnical scenarios.

Keywords: Digital Twin, marine pollution, training, disaster response.

1. Introduction

Marine pollution is one of the biggest problems and threats to the sustainability of our planet. Thus, it is of utmost importance to invest in measures to combat marine pollution that will allow us to achieve a cleaner ocean for future generations [2]. Spills of hydrocarbons or hazardous pollutants can have disastrous consequences that continue to be felt years later [31]. If a spill occurs, there must be a rapid response and collection of the pollutants to minimize the consequences on the environment and marine life. Therefore, the various entities responsible for containing the event must be mobilized and coordinated to minimize the environmental impact, response time, and financial impact.

Mitigating marine pollution requires all parties involved to know the intervention plans and have the appropriate training. It is essential to conduct periodic exercises using the response mechanisms, usually involving real on-site simulations [9]. This scenario makes marine pollution preparation, especially on an international scale, difficult to conduct regularly and opens the possibility of developing digital solutions to improve preparedness and continuously assess the performance of the response network.

Digital Twins, defined as digital replicas of physical assets or systems, can be used to analyze, and simulate different maritime scenarios to make processes more efficient, sustainable, and cost-effective. It is now clear that "*industries such as maritime are moving over to cyber-physical systems, and you cannot verify and classify these only on the basis of documentation – these systems need to be tested in a simulated environment*" [34]. Nevertheless, despite the outstanding ongoing initiatives to develop Digital Twins of the ocean [21, 22], there is still a lack of solutions addressing marine pollution.

Our research is integrated into the international project Marine Pollution Control Simulator (MPCS), aiming to create a learning and simulation tool that allows the development of the skills of the response teams to the occurrence of a spill based on a discrete event simulation methodology. Its main objective is to provide a quick and effective response to the threat or occurrence of a spill of hydrocarbons or other hazardous pollutants to minimize the impact on the environment, the economy, and the localities near the spill location. Developing a marine pollution Digital Twin is one of the critical tasks in the MPCS project and the main research goal addressed in this paper.

The remainder of this paper is organized as follows. The following section reviews previous studies on Digital Twins and their applicability in a maritime environment. Next, Section 3 presents the design research approach. Subsequently, Section 4 describes the Digital Twin model for maritime pollution and its results. The paper closes in Section 5, presenting the main conclusions, limitations, and avenues for future research.

2. Background

2.1. The Emergence of Digital Twins in the Maritime Context

In 1991, David Gelernter presented the concept of Mirror Worlds, which is very close to the Digital Twin concept known today. It consisted of a software model that could be fed with data in real-time to reproduce reality. The model was also capable of recalling past events whenever requested. Although the concept was innovative, it was impossible to implement due to the technological developments when it was presented [11]. Later, in 2002, Michael Grieves associated the term with a model for Product Lifecycle Management [15, 17]. The model comprised three elements: (1) physical space, (2) virtual space, and (3) a linking mechanism that allows information exchange between them [16].

NASA marked the history of Digital Twins when they adopted the concept in Apollo 13, assisting several astronauts in returning home after a mission problem. Much has changed since the Apollo 13 launch, but Digital Twin has increased its potential to predict a physical system state and anticipate future states [32]. This can be accomplished thanks to the bidirectional data exchange between the physical and the digital object [32]. Recently, Tao [36] proposed a Digital Twin Model composed of five dimensions as an extension to the three-dimension model introduced by Grieves. The author suggests an approach where the model combines physical and virtual data for a more thorough and precise information collection. This model also includes services where the DT functions can be encapsulated to allow centralized management and immediate access [36].

Depending on the data integration, Kritzinger [25] claims three different subcategories of Digital Twins exist. Fig.1 presents the subcategories proposed. A Digital Model exists if there is no automated data transfer between the digital and physical object. On the other hand, a Digital Shadow results from a unidirectional data exchange between a physical and a digital object. Finally, Digital Twin's data exchange is automated and bidirectional [25].

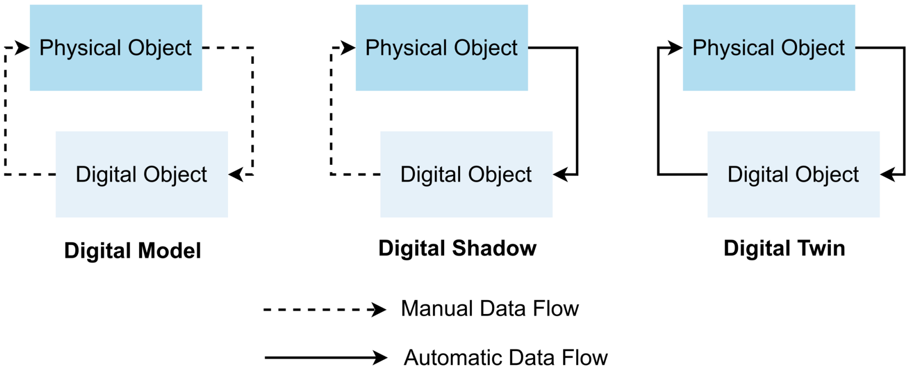


Fig. 1. Digital Twin categories (adapted from [25]).

In recent years, researchers have explored the applicability of Digital Twins in a maritime environment. Lee et al. [26] presented a Digital Twin capable of predicting ocean waves and hydrodynamic performance. This information can help reduce vessel fuel consumption and optimize velocity. The Digital Twin can also find the optimum route and calculate the associated risk in real-time. Coraddu [6] presented a Digital Twin of a ship that can estimate the speed loss caused by marine fouling, which can help reduce fuel consumption by scheduling maintenance actions for cleaning and estimating ship efficiency. However, most of the studies focus on the shipping business, lacking solutions for training all the details of marine pollution control at a large scale.

One of the most inspiring projects for the marine adoption of Digital Twins is currently under development by the European Union: the ILIAD Digital Twin of the Ocean. This project will allow users to visualize the ocean's geography and use virtual or augmented reality to view ocean data more interactively. It will also involve other European projects [21, 22]. Mercator Ocean International is also developing a model for the ocean that will be combined with other frameworks for real-time operations, allowing for the past, present, or future ocean state to be represented [27]. A Digital Twin pilot for the Cretan Sea is being developed as part of the ILIAD project. It aims to help track and forecast contamination from an oil spill by combining several high-resolution forecasting services [35]. This project confirms the novelty of the topic and the opportunity to go beyond the ILIAD vision, not only forecasting oil spills but also using the Digital Twin to train the multidisciplinary teams responsible for pollution-fighting.

2.2. Preparing for Disaster Response

Disaster response training can use scenario-based simulations, where personnel can make the same decisions as in real scenarios [24]. The training of disaster response personnel should focus on speedy response and team coordination, which implies knowledge of the combat protocol [24]. To achieve these goals, response teams must exercise regularly to build and assess preparedness. It is important to identify the main capabilities that should be assessed and how to evaluate users' performance against them during the exercise [13]. According to [13], there are three types of capabilities: functional, management and support, and relational and problem solving. The author also identifies evaluation techniques that can be used to evaluate user performance, such as after-action review, indicators, documentation, and plan evaluation. The requirements and boundaries of digital crisis management tools have already been addressed in recent ISD research. For example, [3] studying the process support, the timeline of exercises, ease-of-use, and flexibility. Another example of information sharing during a crisis is presented by [29].

2.3. Existing Tools for Management and Performance Evaluation in Marine Pollution

Simulation replicates or produces real-world experiences interactively so that the user can practice certain real-life aspects and make decisions in a controlled and close-to-real environment [10, 33]. This kind of user experience allows for using software simulators as a platform for training. Users can use them to develop their skills and coordination strategies [20]. Training is essential for developing appropriate knowledge and skills for emergency response situations and should occur regularly. Therefore, simulators are a handy way to train response teams and are less expensive than traditional training [33].

Simulators of dangerous events have been created for numerous fields, like aviation, military training, and surgery [20, 23]. There are also simulators developed for the maritime environment. For example, the Transas NTPro 5000 version 5.35 navigational bridge simulator [18]. According to the study presented in [18], this simulator provided better results than conventional training methods and helped users improve their navigation and oil recovery skills. The Emulator is another example that allows training in different situations, like marine pollution prevention [12].

Dashboards are another vital tool for understanding how training exercises are conducted. According to [8], a dashboard is "*a visual display of the most important information needed to achieve one or more objectives; consolidated and arranged on a single screen so the information can be monitored at a glance*". The author also presents some fundamental characteristics that should be found on dashboards. The first aspect referred to is that the information presented on a dashboard should be well summarized so the user can immediately understand it. Similarly, the display of this information should be concise, clear, intuitive, and customized to the user.

Combining simulation capabilities and advanced visual representations of complex events like marine pollution is a central requirement for Digital Twins. Key performance indicators need to be collected regularly, allowing the visualization of the evolution of data through time. These metrics are essential for quality control; however, it is crucial to identify relevant and adequate performance indicators in the problem's context [9]. Performance evaluation is vital in systems with a robust educational component since the user's learning depends on the feedback given [1]. However, our research revealed that existing marine pollution simulators (e.g., OpenDrift [7], PISCES II [5], SIMREC [38], GNOME Suite for Oil Spill Modeling [30]) require improvement in dashboard capabilities and focus on the performance of reducing the contaminant (e.g., amount of oil removed, areas affected at the end of the exercise), lacking sufficient features to understand the social communication during the event (e.g., the messages were clear, the participants knew who was involved and what needed to be done, the areas were adequately identified during the planning phase) and response protocol evaluation (e.g., the process of authorizations was accomplished as required). A Digital Twin can provide a solution to evaluate the complex sociotechnical scenario of marine pollution control.

3. Research Approach

Our work follows the design science research (DSR) paradigm, aiming to propose innovative solutions for a problem, producing knowledge from the design process [19]. The artifacts' utility is central to DSR and may include models, instantiations, or methods iteratively developed in sociotechnical contexts [19]. On the one hand, DSR requires a solid knowledge base to inform the design and evaluation. On the other hand, the applied nature of DSR also requires a relevant context [14]. Fig. 2 presents our DSR grid [4] .

problem A Digital Twin is necessary to replicate the real environment of marine pollution. Existing proposals are limited in training social intervention.	*research process* Steps of problem formulation, design, and summative evaluation. Adoption of DSR guidelines in the process.	*solution description* IT artifact with simulation, forecasting, and performance evaluation capabilities incorporated into an international platform for marine pollution training.
input knowledge Marine pollution control, simulation systems, Digital Twin architecture, and crisis response preparedness.	*concepts* Information systems; Large scale Digital Twin; Dashboard.	*output knowledge* Design requirements and a guiding model for marine pollution Digital Twin.

Fig. 2: DSR grid for the development of marine pollution digital twin.

The DSR grid [4] summarizes the main elements of DSR projects. Our work aims to produce prescriptive knowledge with a model and an instantiation [14] beneficial to different stakeholders of marine pollution in national and international waters. The problem formulation phase occurred in 2022 with the proposal of an international cooperation project for marine pollution control. The design and development include a team of eight developers, five researchers, and multiple marine experts, having weekly meetings and producing different project deliverables to ensure the solution is consistent with the project's needs. The model development and the instantiation of the simulation capabilities are completed. However, the evaluation is only partially done by the experts, requiring all the modules of the system integrated to be completed. Nevertheless, relevant knowledge was already produced at this stage, as presented in the following section.

4. Results

4.1. Design and Development

The first stage of development of the MPCS consisted of gathering the system requirements, which resulted in the preparation of a deliverable. Examples of requirements include "*the mathematical model should provide the simulation, for each instant of time, with all relevant oil spill data (...) and the hydrodynamic and meteorological database should provide the simulation with the sea conditions (...) and the state of the atmosphere (...).* Also "*the hydrodynamic and meteorological data should be actual data that occurred in the time interval, some years ago, and in the geographical area, in which the exercise takes place*". In marine pollution response, "*it is important (...) to forecast the drift of the spill, the sea state and the atmosphere.(...)*". "*A naval or aerial means, when approaching the event and/or oil spill site, should automatically report (without user intervention), depending on its location and spill evolution, the information provided by the mathematical model of the MPCS.(...)*".

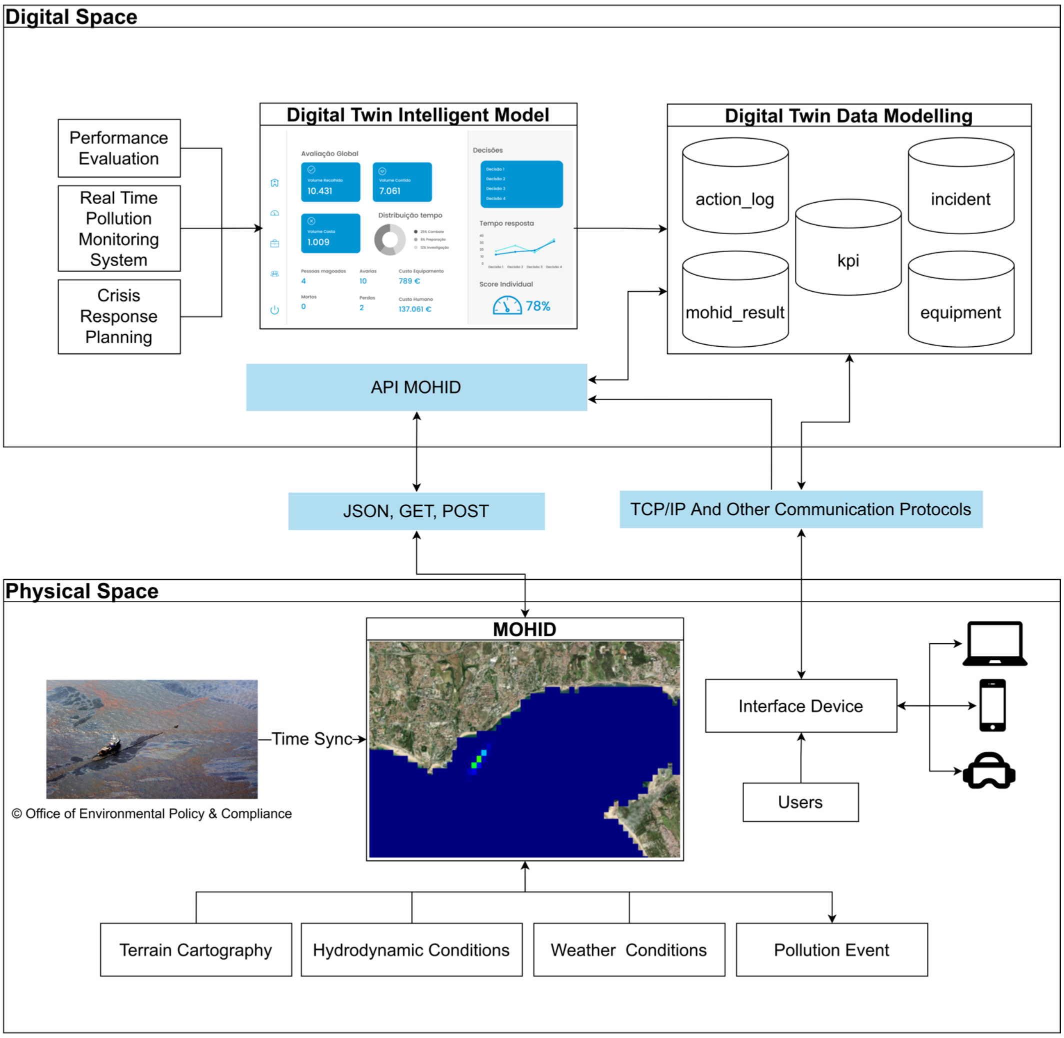


Fig. 3. Digital Twin model for training marine pollution control.

The Digital Twin aims to enhance the capacity for coordination, response, and experience, individually and collectively, in maritime pollution control actions and to assess the user's performance in the exercise. The framework presented by [37] inspired our proposal for the Digital Twin model for maritime pollution (Fig. 3). It is divided into three modules: data capture, DT Intelligent Model, and DT data [37]. The model is split into physical and digital spaces and data exchange [11]. In the physical space, there is the occurrence of an oil spill and the data capture. The digital space contains the data module and the intelligent module.

The data capture module is responsible for collecting data from the physical space. In our context, this physical space is instantiated using real data from the coast of the Iberian Peninsula, presented at the bottom: cartography, hydrodynamics, weather, and pollution location, captured over a month. When this module receives a report of an oil spill and its characteristics, it calculates its evolution until the exercise's end time. This module uses MOHID algorithm [28] and real weather and oceanographic conditions collected in the past to predict hydrocarbon evolution. The team chose this software since there were already persons with knowledge of the tool, and communication with MOHID's developers was possible. Therefore, this DT presents the particularity of using "real physical conditions" that occurred in the past to assist in preparing teams responsible for pollution control. Users can use booms, skimmers, chemical dispersants, and other types of equipment to contain and collect the pollutant. The DT receives an alert whenever a user interferes with the current state by placing equipment to collect hydrocarbon. It automatically calculates the impact that this change has on the environment and it is also possible to get a satellite image (Fig. 4) of the training setting.

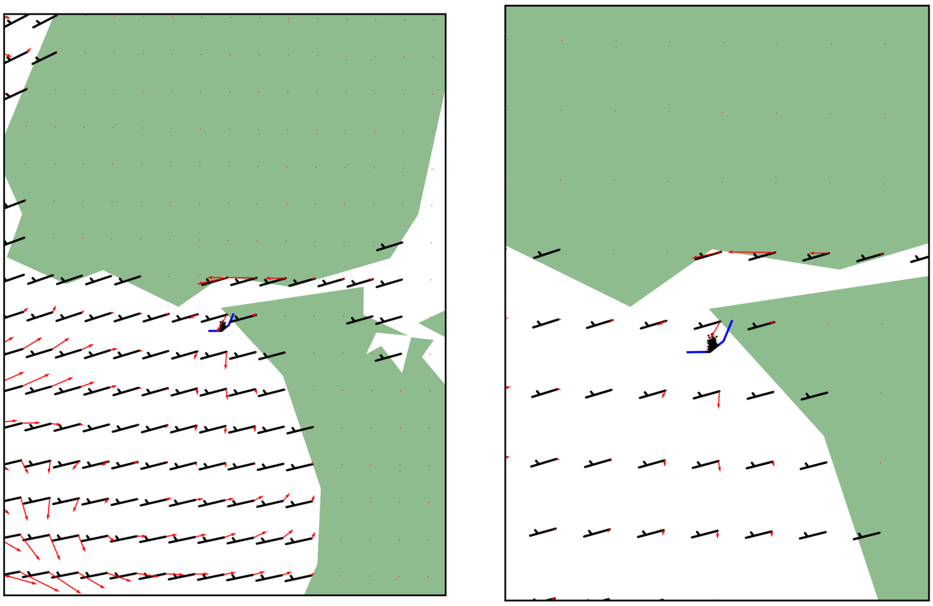


Fig. 4. Satellite images

Fig. 4 represents satellite images users can request to obtain the current spill's state at any moment of the exercise. The image on the right is zoomed in to allow for a better perception of the scenario. The DT generated the satellite images after the barrier placement to contain the spill. The barrier is represented in Fig. 4 with a blue line and contains the spill represented as black dots. When a user requests a satellite image, they can also request information about the wind direction (represented with black lines) and ocean current (represented with red arrows), similarly to a request made to an aerial vehicle monitoring the region (e.g., navy helicopter). Satellite imagery can be requested at any time but is particularly useful to aid the placement of spill containment equipment since by having visual information on wind direction and ocean current, the user can acquire insight into the future evolution of the pollution impact.

The Digital Twin intelligent module can do real-time monitoring and performance evaluation. Real-time monitoring allows users to keep track of the spill's evolution over time (e.g., what changed after the decision to put a specific type of barrier, compared to the option of no barrier). Users can keep track in real-time of some indicators of the pollutant, like the volume on the coast, collected, dispersed, and evaporated. The other primary function of this module is to calculate individual users' performance and global performance. The users' assessment is based on their decision-making and timing. Global evaluation of the exercise depends on individual performance, participant coordination, and some metrics like volume collected and human and equipment costs.

4.2. Proof of Concept Demonstration

To simulate marine pollution conditions, a three-dimensional water modeling system is used. As represented in Fig. 3 the DT physical conditions include terrain cartography, real weather data, and hydrodynamic conditions, and data from the pollution event to calculate its evolution through time. The weather data and hydrodynamic conditions date from October 2021 and were collected at the location defined as the source of the spill. The use of real data, even if not obtained in real time, allows a more reliable and close-to-the-real simulation of the pollution event. At the beginning of the exercise, the MPCS Manager defines the pollution event (e.g., volume and type of hydrocarbon, location, type of incident). Fig. 5 shows an example of the pollution impact without team intervention.

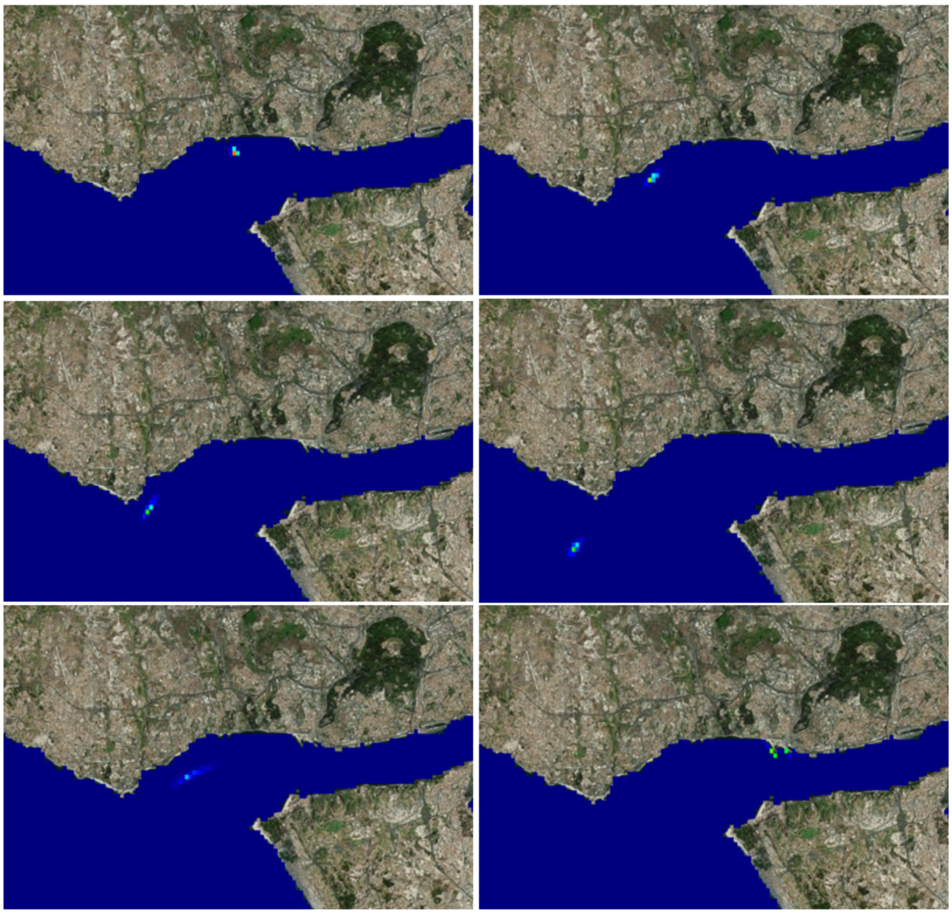
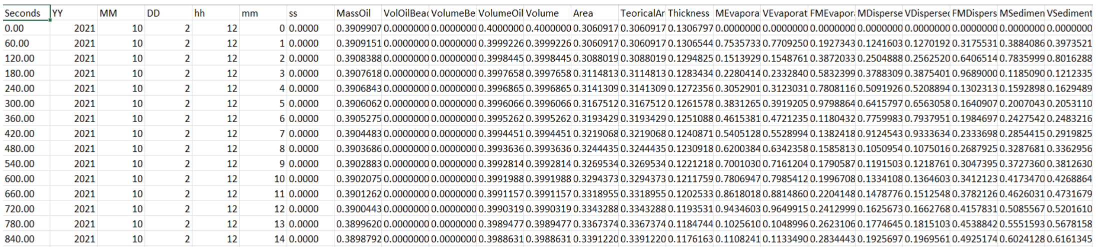


Fig. 5. Oil spill evolution.

Several metrics can be obtained to reveal the system's real-time tracking and calculate users' performance. For real-time tracking, it is necessary to save and keep track of the volume of oil that reaches the shore, oil properties (e.g., density, volume) as its characteristics change over time, and the coordinates of the polygon that define the spill area. Other MPCS modules (e.g, virtual reality) use the event's location to create a 3D representation of the pollution site.

All communications are stored in the database to assist a complete event timeline. For example, authorization requests, notification to other users, decisions taken, and errors (e.g., trying to start the pollution control ship not having all the necessary users within the range, operating equipment lacking proper training, among other situations identified by the experts). At this stage, the evaluation of protocol compliance is done at the end of the exercise, but it will be possible to explore natural language processing in the future to identify possible problems in protocol execution (e.g., contacting the wrong person to request instructions). An example of data stored over time is shown in Fig.6. This file contains essential information about the volume of oil beached, volume of oil evaporated, dispersed, sedimented, dissolved, volume removed by chemical dispersion and mechanical recovery, among other information about the physical space.

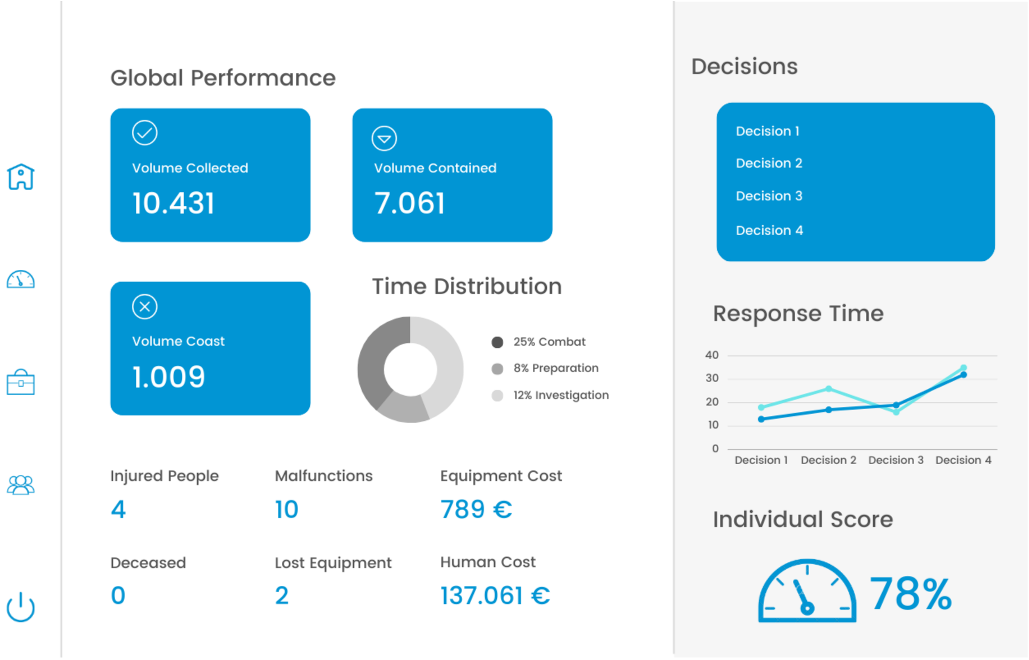


Seconds	YY	MM	DD	hh	mm	ss	MassOil	VolOilBeac	VolumeBe	VolumeOil	Volume	Area	TeoricalAr	Thickness	MEvapora	VEvaporat	FMEvapor	MDisperse	VDispersec	FMDispers	MSedimen	VSediment
0.00	2021	10	2	12	0	0.0000	0.3909907	0.0000000	0.0000000	0.4000000	0.4000000	0.3060917	0.3060917	0.1306797	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000
60.00	2021	10	2	12	1	0.0000	0.3909151	0.0000000	0.0000000	0.3999226	0.3999226	0.3060917	0.3060917	0.1306544	0.7535733	0.7709250	0.1927343	0.1241603	0.1270192	0.3175531	0.3884086	0.3973521
120.00	2021	10	2	12	2	0.0000	0.3908388	0.0000000	0.0000000	0.3998445	0.3998445	0.3088019	0.3088019	0.1294825	0.1513929	0.1548761	0.3872033	0.2504888	0.2562520	0.6406514	0.7835999	0.8016288
180.00	2021	10	2	12	3	0.0000	0.3907618	0.0000000	0.0000000	0.3997658	0.3997658	0.3114813	0.3114813	0.1283434	0.2280414	0.2332840	0.5832399	0.3788309	0.3875401	0.9689000	0.1185090	0.1212335
240.00	2021	10	2	12	4	0.0000	0.3906843	0.0000000	0.0000000	0.3996865	0.3996865	0.3141309	0.3141309	0.1272356	0.3052901	0.3123031	0.7808116	0.5091926	0.5208894	0.1302313	0.1592898	0.1629489
300.00	2021	10	2	12	5	0.0000	0.3906062	0.0000000	0.0000000	0.3996066	0.3996066	0.3167512	0.3167512	0.1261578	0.3831265	0.3919205	0.9798864	0.6415797	0.6563058	0.1640907	0.2007043	0.2053110
360.00	2021	10	2	12	6	0.0000	0.3905275	0.0000000	0.0000000	0.3995262	0.3995262	0.3193429	0.3193429	0.1251088	0.4615381	0.4721235	0.1180432	0.7759983	0.7937951	0.1984697	0.2427542	0.2483216
420.00	2021	10	2	12	7	0.0000	0.3904483	0.0000000	0.0000000	0.3994451	0.3994451	0.3219068	0.3219068	0.1240871	0.5405128	0.5528994	0.1382418	0.9124543	0.9333634	0.2333698	0.2854415	0.2919825
480.00	2021	10	2	12	8	0.0000	0.3903686	0.0000000	0.0000000	0.3993636	0.3993636	0.3244435	0.3244435	0.1230918	0.6200384	0.6342358	0.1585813	0.1050954	0.1075016	0.2687925	0.3287681	0.3362956
540.00	2021	10	2	12	9	0.0000	0.3902883	0.0000000	0.0000000	0.3992814	0.3992814	0.3269534	0.3269534	0.1221218	0.7001030	0.7161204	0.1790587	0.1191503	0.1218761	0.3047395	0.3727360	0.3812630
600.00	2021	10	2	12	10	0.0000	0.3902075	0.0000000	0.0000000	0.3991988	0.3991988	0.3294373	0.3294373	0.1211759	0.7806947	0.7985412	0.1996708	0.1334108	0.1364603	0.3412123	0.4173470	0.4268864
660.00	2021	10	2	12	11	0.0000	0.3901262	0.0000000	0.0000000	0.3991157	0.3991157	0.3318955	0.3318955	0.1202533	0.8618018	0.8814860	0.2204148	0.1478776	0.1512548	0.3782126	0.4626031	0.4731679
720.00	2021	10	2	12	12	0.0000	0.3900443	0.0000000	0.0000000	0.3990319	0.3990319	0.3343288	0.3343288	0.1193531	0.9434603	0.9649915	0.2412999	0.1625673	0.1662768	0.4157831	0.5085567	0.5201610
780.00	2021	10	2	12	13	0.0000	0.3899620	0.0000000	0.0000000	0.3989477	0.3989477	0.3367374	0.3367374	0.1184744	0.1025610	0.1048996	0.2623106	0.1774645	0.1815103	0.4538842	0.5551593	0.5678158
840.00	2021	10	2	12	14	0.0000	0.3898792	0.0000000	0.0000000	0.3988631	0.3988631	0.3391220	0.3391220	0.1176163	0.1108241	0.1133490	0.2834443	0.1925697	0.1969561	0.4925174	0.6024128	0.6161345

Fig. 6. Marine pollution data (extract).

It is essential to differentiate between individual and team results for the performance evaluation, defining indicators for both. Thus, data such as time (preparation phase, combat phase, investigation phase, and total), the volume of hydrocarbons collected and contained, human/equipment cost, people injured or deceased, number of malfunctions, and number of losses were identified as global performance indicators by the team.

For the evaluation of individual performance, the response time and decisions taken by the users (evaluated in the system log at the end) are identified. One of the goals of the exercise is to help system users improve performance and knowledge of standard protocols, so these metrics help understand some of the points of failure improvement measures. Fig. 7 presents a mockup of the performance evaluation dashboard.



Global Performance

Volume Collected
10.431

Volume Contained
7.061

Volume Coast
1.009

Time Distribution

Injured People
4

Malfunctions
10

Equipment Cost
789 €

Deceased
0

Lost Equipment
2

Human Cost
137.061 €

Decisions

Decision 1
Decision 2
Decision 3
Decision 4

Response Time

Individual Score
78%

Fig. 7. Digital Twin dashboard.

Fig. 7 highlights the global performance (on the left) and the individual performance on the right. A list of individual user decisions is displayed, a graph with the response time for each decision made by the user, and an individual score. The DT data module manages how the data is stored and presented in the database.

Configuration of the simulation exercise and persistence of the exercise state (a marine pollution event may take weeks to complete) is achieved with the DT data module. The database includes a log record for tracking and analyzing exercise performance for information on improving operational coordination. The log record also allows for tracking whether the protocol is being followed and provides feedback on user choices and their impact (e.g., if a boom is used under conditions that do not follow the recommended procedure, it can greatly impact the volume collected or response time). Based on the DT data module, we can also evaluate the performance against a base case without human intervention. Similarly, verifying the users evolution by comparing their performance of previous exercises is also possible.

The DT model implementation will also include e-learning modules covering topics such as regulations, legislation, technologies, equipment, methodologies, leadership in marine pollution control, and operation and administration of the MPCS. Each module includes a video lesson, a presentation, a document with information on the topic under assessment, and a self-assessment test to enable individual and autonomous training.

Our proposal allows us to create exercises aligned with the International Maritime Organization's (IMO) priorities, namely, to practice international coordination in marine pollution control, standardize procedures among countries and optimize results. It will also regularly train national and international marine pollution teams in three essential dimensions: coordination of the means involved, communication, procedures (e.g., requesting support from European structures), and equipment maintenance.

The proof of concept confirmed the suitability of the DT module to represent all the critical conditions necessary for a natural environment for training and performance evaluation. The new framework allows users to train in coordination and understand failure points in this exercise. This helps improve emergency response when a real-life oil spill occurs, as users know what procedures to follow. At this research stage, however, it is impossible to make a final evaluation as not all modules are integrated (e.g., training configuration, VR, or e-learning). Therefore, we presented insights collected at this stage about the evaluation of the DT, highlighting requirements and compliance with best practices and international standards for marine pollution control, confirmed by the specialists participating in the project.

4.3. Design Principles

The reflection made during this stage of our DSR allowed us to devise the following design principles for DTs in marine pollution scenarios.

Design principle 1: *Digital Twins for pollution control should provide real time feedback about the impact of decisions.* During requirements analysis, we gather evidence that response teams need to know the impact of their actions as soon as possible to apply corrective measures.

Design principle 2: *Assessing marine pollution control performance can include quantitative measurements based on impact prediction and qualitative analysis.* Through contacts with experts, it was possible to identify relevant indicators of physical impact (e.g., volume of pollutant extracted and volume of pollutant reaching the shore). The relevance of post-event analysis for reflection was also verified, requiring details about the context of the decisions taken (through the analysis of log files).

Design principle 3: *Interoperability of the physical model and the components responsible for interacting with users.* During the execution of the exercise, it is necessary to ensure access to the data obtained with the physical model (e.g., spill and barrier location and aerial photography of the incident site) in an interoperable manner.

Design principle 4: *The Digital Twin can be complemented with the e-learning platform to provide the concepts needed by the system users.* The Digital Twin and learning content teams must work aligned to ensure the correct acquisition of the knowledge required for learning and training (for example, protocol knowledge).

Design principle 5: *Digital Twin should make it possible to forecast pollution behavior.* User actions directly or indirectly influence the state of the spill, so the Digital Twin must be able to predict its future state at every instant.

Design principle 6: *The Digital Twin must ensure the persistence of data from previous exercises.* It is extremely important to keep data from previous sessions to assess the evolution of user performance.

5. Conclusion

This paper presented a Digital Twin proposal for marine pollution control. The results include the Digital Twin model, the construction of the simulation layer, and the design of the performance evaluation and visualization layers. Our work extends the current body of knowledge in information systems for marine pollution by incorporating the sociotechnical training elements usually absent in traditional simulators. The modular MPCS architecture puts the Digital Twin at the core of the entire exercise, creating a digital replica of a region affected by pollution, the assets, the people, and the information system. For theory, our contribution is in the proposal of a Digital Twin for a complex sociotechnical context at a regional scale, with training purposes, not restricted to the traditional use of specific assets.

There are also important limitations that must be presented. First, the results were obtained during the project's first year and aimed at identifying all the Digital Twin's variables, elements, and interactions. However, the end users did not yet test it in real marine pollution training. The researchers and marine pollution experts did the evaluation with a proof of concept. Second, the Digital Twin needs to create an extensive log of all the scenarios that emerge due to the decisions made by the users. For example, when a barrier is placed or when a specific pump is selected, it is necessary to compare it with the optimum solution (or previous exercises to understand if the team performed better). Moreover, all the information exchanges are stored in the log. Only when the entire system is complete will it be possible to evaluate if the model is sufficient to support the training and evaluation of all the participants according to their role in the event. Finally, The Digital Twin is a part of the system that also includes VR interaction by the participants (e.g., local authorities, European Maritime Safety Agency (EMSA), port authorities, and intervention team), which is out of the scope of this paper.

The next steps toward constructing the Digital Twin include the integration with the other modules that are under development. For the performance evaluation, several alternatives will be explored, for example, performance evaluation based on the previous exercise, based on the percentage of pollution removed, based on an optimum decision tree, and based on the simulation result without human interference. Another idea that will be explored is to provide individual feedback and a retrospective at the end of the exercise to elucidate users of their points of failure. Future work can integrate multiple Digital Twins (e.g., the ship Digital Twin, pump Digital Twin, and human Digital Twin) operating in an integrated environment. This vision is aligned with the recent standard ISO 23247-1:2021 (Digital Twin framework for manufacturing), which envisions more complex scenarios aggregating different Digital Twins that need to communicate. A combination of multiple interoperable Digital Twins opens new prospects for training complex emergency response scenarios, where user preparation is vital.

Acknowledgments

This work was partially funded by MPCS project #101048546 under UCPM-2021-PP-MARIPOL, programme UCPM2027 and by the FCT - Foundation for Science and Technology, I.P./MCTES through national funds (PIDDAC), within the scope of CISUC R&D Unit - UIDB/00326/2020 or project code UIDP/00326/2020.

References

1. Bellotti, F., Kapralos, B., Lee, K., Moreno-Ger, P., Berta, R.: Assessment in and of Serious Games: An Overview. Advances in Human-Computer Interaction. 2013 1–1 (2013)
2. Bellou, N., Gambardella, C., Karantzalos, K., Monteiro, J.G., Canning-Clode, J., Kemna, S., Arrieta-Giron, C.A., Lemmen, C.: Global assessment of innovative solutions to tackle marine litter. Nat Sustain. 4 (6), 516–524 (2021)
3. Bellström, P., Persson, E., Magnusson, M.: Elaborating requirements for a digital crisis training tool: Findings from a pilot study. In: Proceedings of the 28th International Conference on Information Systems Development: Information Systems Beyond 2020, ISD 2019. (2019)
4. Vom Brocke, J., Maedche, A.: The DSR grid: six core dimensions for effectively planning and communicating design science research projects. Electronic Markets. 29 379–385 (2019)

5. California State University Maritime Academy: Pisces II - CSUM, https://www.csum.edu/industry/simulation-center/pisces.html, Accessed: May 01, 2023
6. Coraddu, A., Oneto, L., Baldi, F., Cipollini, F., Atlar, M., Savio, S.: Data-driven ship digital twin for estimating the speed loss caused by the marine fouling. Ocean Engineering. 186 106063 (2019)
7. Dagestad, K.-F., Röhrs, J., Breivik, Ø., Ådlandsvik, B.: OpenDrift v1.0: a generic framework for trajectory modeling. Geosci Model Dev. 11 (4), 1405–1420 (2018)
8. Few, S.: Dashboard Confusion. (2004)
9. Fitz-Gibbon, C.Taylor.: Performance indicators. Multilingual Matters (1990)
10. Gaba, D.M.: The future vision of simulation in health care. BMJ Qual Saf. 13 (Suppl 1), i2–i10 (2004)
11. Gelernter, D.: Mirror worlds: Or the day software puts the universe in a shoebox... How it will happen and what it will mean. Oxford University Press (1993)
12. GEMTQ: Simulator crisis management and the prevention and control of... | The General Organization for Maritime Training, http://www.gemtq.edu.sy/simulators/3?change_language=en, Accessed: May 01, 2023
13. Greenberg, B., Voevodsky, P., Gralla, E.: A Capabilities-Based Framework for Disaster Response Exercise Design and Evaluation: Findings from Oil Spill Response Exercises. J Homel Secur Emerg Manag. 13 (4), (2017)
14. Gregor, S., Hevner, A.R.: Positioning and presenting design science research for maximum impact. MIS Quarterly. 337–355 (2013)
15. Grieves, M., Vickers, J.: Digital twin: Mitigating unpredictable, undesirable emergent behavior in complex systems. Transdisciplinary Perspectives on Complex Systems: New Findings and Approaches. 85–113 (2017)
16. Grieves, M.W.: Product lifecycle management: the new paradigm for enterprises. International Journal of Product Development. 2 (1–2), 71–84 (2005)
17. Grieves, M.W.: Virtually Intelligent Product Systems: Digital and Physical Twins. American Institute of Aeronautics and Astronautics, Inc. (2019)
18. Halonen, J., Lanki, A.: Efficiency of maritime simulator training in oil spill response competence development. TransNav: International Journal on Marine Navigation and Safety of Sea Transportation. 13 (1), 199–204 (2019)
19. Hevner, A.R., March, S.T., Park, J., Ram, S.: Design science in information systems research. MIS Quarterly. 28 (1), 75–105 (2004)
20. Hvannberg, E.T.: A Framework for Monitoring Evolution and its Drivers in Training Simulators. The Journal of Interaction Science. 7 19–19 (2019)
21. Igor Stefan Mayer: Digital Twins for the Real World. (2022)
22. Iliad: Home | Iliad - Digital Twin of the Ocean, https://www.ocean-twin.eu/, Accessed: April 15, 2023
23. José Sánchez-Ledesma, M., Juanes, J.A., Bautista, C., Miranda, D., Sancho, C., Gonçalves, J.M.: A simulation environment using a simulator mannequin for the acquisition of skills by medical students in traumatic brain injury. In: Proceedings of the 3rd International Conference on Technological Ecosystems for Enhancing Multiculturality. pp. 59–64. Association for Computing Machinery (2015)
24. Klein, M.G., Jackson, P.L., Mazereeuw, M.: Teaching humanitarian logistics with the Disaster Response Game. Decision Sciences Journal of Innovative Education. 20 (3), 158–169 (2022)
25. Kritzinger, W., Karner, M., Traar, G., Henjes, J., Sihn, W.: Digital Twin in manufacturing: A categorical literature review and classification. Ifac-PapersOnline. 51 (11), 1016–1022 (2018)
26. Lee, J.H., Nam, Y.S., Kim, Y., Liu, Y., Lee, J., Yang, H.: Real-time digital twin for ship operation in waves. Ocean Engineering. 266 (2022)
27. Mercator Ocean: Digital Twin of the Ocean - Mercator Ocean, https://www.mercator-

ocean.eu/en/digital-twin-ocean/, Accessed: April 15, 2023

28. MOHID: MOHID Water Modelling System, http://www.mohid.com/, Accessed: January 13, 2023
29. Nespeca, V., Comes, T., Alfonso, L.: Information sharing and coordination in collaborative flood warning and response systems. In: Proceedings of the 27th International Conference on Information Systems Development: Designing Digitalization, ISD 2018. (2018)
30. NOAA: GNOME Suite for Oil Spill Modeling | response.restoration.noaa.gov, https://response.restoration.noaa.gov/gnomesuite, Accessed: May 01, 2023
31. NOAA: Oil spills | National Oceanic and Atmospheric Administration, https://www.noaa.gov/education/resource-collections/ocean-coasts/oil-spills, Accessed: April 27, 2023
32. Piascik, B., Vickers, J., Lowry, D., Scotti, S., Stewart, J., Calomino, A.: Draft materials, structures, mechanical systems, and manufacturing roadmap: Technology area 12. (2010)
33. Rudinsky, J., Hvannberg, E.T.: Consolidating Requirements Analysis Models for a Crisis Management Training Simulator. In: ISCRAM. (2011)
34. Smogeli, Ø.: Digital twins at work in maritime and energy. DNV-GL Feature. 1 (7), (2017)
35. Spanoudaki, K., Kozyrakis, G., Metheniti, V., Parasyris, A., Kampanis, N.: The Cretan Sea oil spill Digital Twin pilot for the ILIAD Digital Twin of the Ocean. Copernicus Meetings (2023)
36. Tao, F., Zhang, M., Liu, Y., Nee, A.Y.C.: Digital twin driven prognostics and health management for complex equipment. Cirp Annals. 67 (1), 169–172 (2018)
37. Wang, K.J., Lee, Y.H., Angelica, S.: Digital twin design for real-time monitoring – a case study of die cutting machine. Int J Prod Res. 59 (21), 6471–6485 (2021)
38. Xamk: SIMREC - Simulators for improving Cross-border Oil Spill Response in Extreme Conditions - Xamk, https://www.xamk.fi/en/research-and-development/simrec-simulators-for-improving-cross-border-oil-spill-response-in-extreme-conditions/, Accessed: May 01, 2023