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Article

Assessing Port Facility Safety: A Comparative Analysis of Global Accident and Injury Databases

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Abstract

Maritime transportation plays a vital role in international trade and commerce, with ports serving as critical points of connection between land and sea transportation systems. The operational efficiency of port facilities is essential to ensure the uninterrupted flow of goods and services, making port safety a top priority for governments, authorities, and shipping companies. Due to the importance of Occupational Health and Safety (OHS) within port environments, it is crucial to develop a structured framework in order to collect and analyze port accidents data. Today there are several different national agencies, private organizations, and/or local regulatory bodies taking charge of these data over different areas, each with variations in how they document and classify the events; in addition these are frequently limited to only major disasters and/or summary statistics. This paper aims to create a general framework to collect and fuse open-source port accident data from different sources in a structured way and to analyze the safety conditions of port facilities by conducting a comparative evaluation based on design of experiment (DoE). Through this analysis, we identify common causes of accidents and injuries in port facilities, as well as any differences in safety conditions across regions, types of port facilities, and other relevant factors. This information can be used to inform policies and practices aimed at improving port safety, reducing accidents and injuries, and ultimately enhancing the efficiency and sustainability of maritime transportation systems. The motivation to develop this research relies on the necessity to define requirements for the development of innovative solutions to be developed by the authors using modeling and simulation (M&S) and XR (extended reality) in order to increase safety in these contexts.

Keywords: port facilities; occupational health and safety (OHS); design of experiment (DoE); multiple correspondence analysis (MCA); training simulation

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1. Introduction

Maritime transportation is a fundamental component of global trade and commerce, with ports serving as critical hubs linking land and sea transportation systems. Today's supply chains operate on a global scale, with continuous flows of goods circulating worldwide. The expansion of ports—together with the growth of surrounding urban areas—has generated substantial benefits in terms of economic development, job creation, and international trade. However, these densely populated and industrialized areas are also exposed to significant risks, such as the release of hazardous materials and fire and explosion events. In both cases, the efficiency and safety of port operations may be severely compromised.

The increasing volume of global trade introduces new challenges to competitiveness, requiring ports to maintain high efficiency through optimized operations. The effective management of port facilities is therefore essential to ensure the uninterrupted flow of goods and services [1,2]. Yet the handling and movement of cargo represent constant sources of risk for operators, who often work in hazardous environments. Maritime and port operations are conducted continuously—day and night and throughout the year—under complex and variable conditions influenced by weather, visibility, and traffic intensity. Port accidents encompass a wide range of events occurring in terminals, harbor facilities, and on-shore industrial plants [3]. For this reason, accident prevention is a key priority for governments, port authorities, and shipping companies seeking to improve system resilience and protect workers, assets, and communities [4–6].

Several authors have examined safety challenges in port settings, highlighting how accidents may arise from interactions among machinery, hazardous cargo, environmental conditions, and human factors [4,7–9]. Historical case studies, including the Texas City (1947), Tianjin (2015), and Beirut (2020) explosions, further demonstrate the potentially severe consequences of incidents occurring in port areas, affecting not only port operators but also surrounding urban regions and national economies [10–13].

Despite the relevance of this topic, existing accident data for port facilities remain fragmented. Unlike maritime vessel incidents monitored through standardized International Maritime Organization (IMO) reporting frameworks [14], accident databases for on-shore port operations are frequently dispersed across national authorities and sectoral institutions and vary widely in terminology, classification criteria, and reporting completeness [15–17]. Prior research has also proposed the use of analytics and machine learning to assess accident risks [18–21]; however, such approaches often suffer from limited generalizability, as models are trained on small, localized datasets and are sensitive to noise and reporting inconsistency [22–24]. The resulting lack of comparability across ports and countries represents a significant limitation to both scientific research and safety policy development.

Emerging economies, in particular, face heightened risks due to limited safety protocols, inadequate training, and insufficient monitoring systems. Preventive measures are therefore essential not only to mitigate catastrophic disasters but also to reduce the frequency of everyday accidents that can compromise the stability and reputation of port operations. The port environment constitutes a complex socio-technical system, where multiple endogenous and exogenous factors—such as human performance, logistics coordination, equipment reliability, and environmental conditions—interact dynamically and nonlinearly [25–27]. This complexity complicates the identification of causal relationships and calls for structured analytical frameworks capable of integrating heterogeneous information sources.

The literature highlights the importance of risk prevention and safety performance evaluation in ports, but there is no unified cross-country framework capable of integrating heterogeneous accident data sources and enabling systematic comparative analysis of safety conditions and contributing factors.

This paper addresses this gap by developing a structured framework for collecting, harmonizing, and analyzing accident records from multiple national and institutional archives. The proposed framework fuses port accident data with contextual variables—including traffic intensity, digitization levels, and socio-economic indicators—and applies DoE techniques to identify significant factors influencing accident rates and their interactions.

Therefore, this investigation began by exploring a range of qualitative and quantitative research methods to identify factors contributing to accidents in ports and the effectiveness of preventive measures in developed and emerging areas. Data were collected through a review of the relevant literature and case studies of recent accidents. The results of this study suggest that preventive measures are essential for improving safety in urban ports. Developed countries have successfully implemented comprehensive protocols, training programs, and monitoring systems to minimize the risk of accidents, while emerging areas require significant improvements in these fields. Additionally, regular accidents pose a significant risk to port activities and require constant monitoring and preventive action. The remainder of this article is organized as follows. Section 2 describes the state of the art; Section 3 describes the data sources and the methodology adopted to harmonize and preprocess port accident archives. Section 4 presents the proposed framework and the experimental design used to analyze correlations among accident factors. Section 5 reports the results and discussion of the comparative and multifactor analyses. Section 6 discusses the application of M&S and XR solutions for improving training and decision support in port environments. Finally, Section 7 concludes this study by summarizing key findings and outlining directions for future research.

2. State of the Art

Maritime transportation represents the backbone of global trade and the world economy. More than 80% of international goods by volume are transported by sea, and this percentage is even higher for developing countries [3,20]. Despite the temporary slowdown caused by the COVID-19 pandemic, global maritime freight volumes have shown a steady upward trend over the past two decades according to UNCTAD statistics [12]. Figure 1 illustrates this continuous increase, which, while driving economic growth, has also amplified the exposure of port systems to operational and safety risks. As traffic intensity and competitiveness rise, the complexity of port operations and the potential for accidents proportionally increase, potentially affecting not only port efficiency but also national development and urban safety.

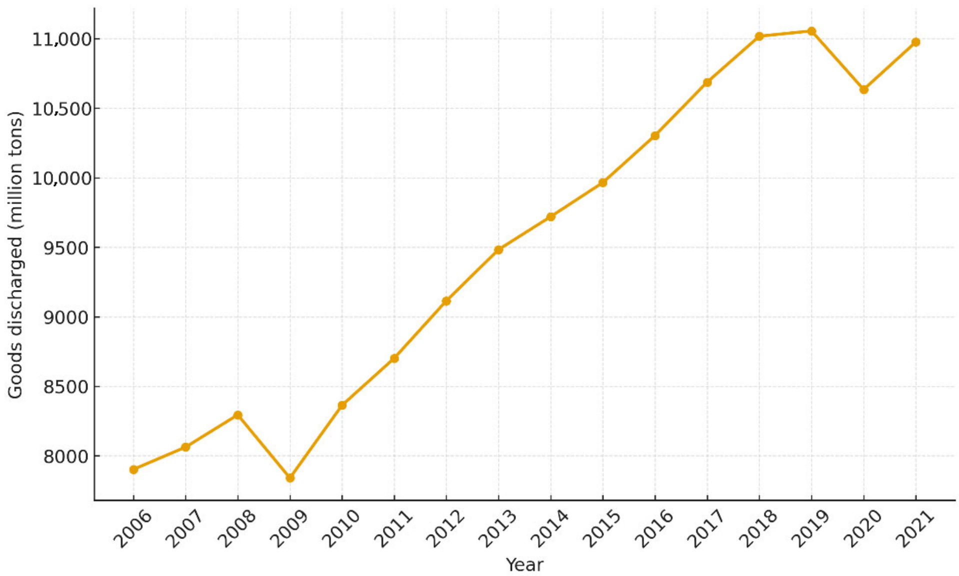

Figure 1. Total goods discharged worldwide (2006–2021).

Historical case studies—such as the explosions in Texas City (1947), Tianjin (2015), and Beirut (2020)—highlight how port-related incidents can produce catastrophic consequences extending far beyond port boundaries, impacting local populations, infrastructure, and economic stability [6,11,17,28]. Although maritime disasters at sea are systematically monitored by the IMO through standardized reporting and continuous regulatory updates [29], comparable monitoring systems for on-shore port facilities are still fragmented. Port-related accidents are typically recorded by national agencies or sectoral authorities with distinct taxonomies, data structures, and reporting procedures. This fragmentation hinders the creation of a consistent, cross-national picture of port safety conditions.

Existing studies on port safety predominantly focus on ship collisions, on-board incidents, and hazardous cargo management [15,16,21,25,30–34]. Others address human factors, environmental conditions, and equipment interaction as key determinants of accident risk [4,7,22,34,35]. While these works provide valuable insights, they usually analyze localized datasets, which vary widely in scope, terminology, and level of detail. A few contributions have attempted to define safety performance indicators or occupational health monitoring systems tailored to maritime environments [15,16,27], yet they have remained limited to national or regional contexts.

A fundamental challenge in advancing maritime safety research lies in the lack of harmonized, large-scale accident datasets. Collecting and integrating data from multiple authorities is essential for designing effective prevention and mitigation strategies [36]. In recent years, data-driven and machine learning (ML) approaches have been increasingly applied to maritime safety, demonstrating their potential to predict accident likelihood and identify risk-prone operational conditions [11,14,19,37]. Algorithms such as SVM, KNN, LightGBM, and XGBoost have been trained using port-specific variables—time, weather, cargo type, temperature, humidity, wind, and current—to estimate accident probabilities [23,38,39]. However, the applicability of these models remains limited: most rely on small or single-port datasets, leading to overfitting and poor generalization across different operational or geographical contexts [21,24,40]. Moreover, neural-network-based models perform suboptimally when trained on heterogeneous or noisy data [6,11], conditions that are typical of multi-country port archives.

The literature therefore reveals two main gaps: (1) the absence of a unified methodological framework for harmonizing port accident data across countries; (2) the need for robust analytical approaches capable of managing heterogeneity, ensuring comparability, and supporting systematic sensitivity analyses of safety factors.

To address these challenges, the present study proposes a structured data-fusion and experimental analysis framework that explicitly tackles the problem of data heterogeneity. The approach combines the following: Extract–Transform–Load (ETL) procedures to ingest data from multiple national repositories and convert them into a common schema; lexical and semantic harmonization using multilingual taxonomy-matching to align inconsistent classification systems; and DoE methods to quantify the effects and interactions among operational, socio-economic, and contextual factors influencing accident rates.

This methodological integration allows for reproducible, cross-country comparisons of safety performance and provides a transparent way to evaluate model robustness against incomplete or non-uniform data sources.

Furthermore, recent advancements in M&S and XR technologies offer powerful tools for enhancing safety performance in port environments. M&S enables the representation of real-world operations—including the behavior of ships, cranes, and workers—and facilitates the assessment of potential hazards, countermeasures, and alternative courses of action (CoAs) [9,41–44]. When combined with XR, simulation environments can be extended into immersive or mixed-reality settings that support training, situational awareness, and decision-making under risk [45,46]. These technologies represent the natural application domain for the analytical results of this study, bridging data-driven analysis and practical safety enhancement through interactive simulation.

In summary, while previous studies have advanced understanding of accident causation in ports, they remain fragmented and largely descriptive. The framework proposed in this paper fills this methodological gap by enabling systematic, harmonized, and comparable analyses of port safety across multiple national datasets. By integrating data-fusion techniques with DoE-based statistical modeling, the approach provides a scalable foundation for evidence-driven safety management, risk mitigation, and the design of simulation-based training systems.

3. Materials and Methods

The methodological framework of this study was designed to enable the comparative analysis of port accident data originating from heterogeneous national sources. The process consisted of four main stages—data acquisition, data harmonization and fusion, contextual integration, and multi-stage DoE analysis—illustrated in Figure 2.

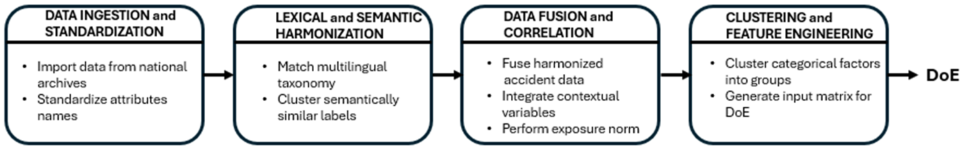

Figure 2. Schematic flow process of the data preprocessing.

It is essential to compile datasets related to safety issues in ports using data from multiple authorities and countries, in order to enable meaningful comparison and understanding of different safety conditions. However, due to national regulations and confidentiality constraints, only limited data are publicly available, and these often differ substantially in content and structure. Because many agencies and institutions maintain their own independent repositories, the resulting datasets are highly non-homogeneous—each characterized by distinct attributes, levels of detail, and reporting methodologies. Moreover, most countries publish their statistical reports only in their national languages, which complicates data retrieval and interpretation. The datasets collected from different authorities are therefore not immediately comparable, as they vary in classification schemes, collection criteria, and resolution. For example, Indian archives classify accidents into ten categories, while Japanese databases adopt twenty-one categories for similar types of events. To enable comparative analysis, it is therefore necessary to gather additional contextual information and reorganize the data into a harmonized structure. To this end, the authors developed a new repository and collection system designed to support dynamic analyses based on open-source data. Port accident records were correlated with supplementary datasets to extract additional insights, normalize diverse reporting conditions, and facilitate cross-country and multi-year comparisons. The integrated dataset incorporates annual trends such as port throughput in seaports, as well as macro-economic indicators (e.g., GDP) and digitization indices. The data collection relied on official statistics from recognized international organizations, including the United Nations [42], together with national agencies and publicly accessible databases from individual countries' regulatory authorities (Table 1).

Table 1. Archives used for processing port accident data.

Country	Source Archive
Hong Kong (HK)	Marine Department of The Government of the Hong Kong Special Administrative Region (2023) [47]
India (IN)	Directorate General Factory Advice Service & Labour Institutes—Ministry of Labour & Employment (2023) [48]
Italy (IT)	INAIL (2023) [49]
Japan (JP)	Japan Industrial Safety & Health Association (JISHA, 2023) [50]
New Zealand (NZ)	WorkSafe—New Zealand Government (2023) [51]
South Africa (ZA)	South African Maritime Safety Authority (SAMSA, 2023) [52]
Turkey (TR)	Social Security Agency of Turkey (SGK, 2023) [53]
USA (US)	U.S. Bureau of Labour Statistics (BLS, 2023) [54]
United Kingdom (UK)	Port Skills and Safety association (PSS, 2023), part of British Ports Association and UK Major Ports Group [55]

The selection of countries for this study was guided by three main criteria: data availability, economic representativeness, and geographic diversity. The chosen cases—Hong Kong, India, Italy, Japan, and the United States—offer sufficiently complete and continuous accident records suitable for multi-year comparison, while also representing distinct stages of industrial and technological development. Hong Kong and Japan exemplify highly digitized port systems in advanced economies; India reflects a rapidly developing maritime sector with increasing automation; Italy provides a representative case of mature European port governance; and the United States contributes long-term, systematically reported data from a large-scale logistics environment.

This composition allows the analysis to cover a spectrum of regulatory frameworks, labor practices, and technological readiness levels, thereby enhancing the robustness of cross-country comparisons. However, the sample also introduces inherent limitations: some regions (e.g., Africa and South America) are underrepresented due to lack of accessible data. As a result, the conclusions should be interpreted as illustrative of global trends rather than universally exhaustive, emphasizing methodological transferability rather than full geographic generalization. The authors developed a repository of correlated and preprocessed data that enables a flexible analytical framework based on comparative evaluation and DoE techniques. The archive was specifically designed to support the investigation of correlations among multiple factors and the implementation of sensitivity analyses. This was accomplished using statistical approaches such as clustering, which allowed the combination of accident causes and types, as well as the correlation of accident data with logistics flows and macro-level indicators characterizing different regions and countries. The data resolution varies significantly among nations. In many cases, available accident reports may or may not include detailed attributes such as the gender and age of victims, their occupation, or other relevant descriptors. Consequently, conducting a fully disaggregated analysis—distinguishing, for example, between occupational roles (e.g., transportation, support activities, stevedoring), causes of injury (e.g., collision, fall, fire), severity of injury, days of absence from work, company size, and temporal distribution of events—is often challenging.

Furthermore, national reporting practices and workplace cultures differ substantially in how meticulously accidents are documented, both in terms of scope and accuracy over time. These inconsistencies affect the overall reliability and comparability of the data. Therefore, one of the most critical tasks of this research involved data fusion, aiming to reconcile and harmonize distinct data sources to make them comparable across countries and institutional contexts.

3.1. Data Ingestion and Standardization

Datasets originating from different authorities (see Table 1) were imported in their original formats (CSV, XLSX, or HTML tables) and converted into a unified schema using ETL procedures. During ingestion, metadata such as data sources, reporting authorities, and publication years were retained as unique identifiers to preserve data provenance. Attribute names were standardized to a controlled set of fields (e.g., event_type, injury_severity, occupation, impact_category, location_type, year).

3.2. Lexical and Semantic Harmonization

Accident attributes often contained inconsistent taxonomies or multilingual labels (e.g., “collisione con oggetto” in Italian vs. “struck by object” in English). To reconcile these discrepancies, a hybrid taxonomy-matching module was implemented. It combines the following:

- String-distance metrics (Levenshtein and Jaro–Winkler similarities) to identify potential lexical matches;
- Embedding-based semantic similarity using pre-trained multilingual language models (Sentence-BERT) for concept-level matching;
- Rule-based expert validation, where ambiguous matches are manually confirmed and logged into a reusable mapping table.

This semi-automated taxonomy alignment allows the system to dynamically detect and map equivalent accident categories across archives without the need for exhaustive manual re-coding. The resulting harmonized taxonomy is stored as a lookup table that ensures the reproducibility and transparency of all mapping decisions.

3.3. Data Fusion and Correlation

Once individual datasets were harmonized, the application performed a vertical fusion of all compatible records into a single integrated repository. During fusion, new relational links were created between accident records and contextual tables containing annual port throughput (TEU) per country and year, macro-economic indicators (GDP per capita), and digitization indices (from UNCTAD and ITU databases). The fusion engine automatically associated each record with its contextual variables through foreign-key joins on [Country, Year], enabling exposure-based normalization and multi-dimensional correlation. All joins and transformations were logged automatically to ensure traceability.

3.4. Clustering and Feature Engineering

To prepare data for comparative and DoE analyses, the fused dataset was enriched through feature engineering. Categorical variables such as occupation, activity type, and injury mechanism were encoded using a hybrid hierarchical clustering algorithm that groups low-frequency categories based on similarity of co-occurrence patterns (e.g., frequency of injury type per job task). An example of the fused dataset can be seen in Table 2. This clustering step prevented data sparsity and allowed balanced comparisons across datasets with different reporting granularities. Additionally, continuous exposure variables (e.g., TEU, GDP, digitization) were normalized by min–max scaling and discretized into three levels (low, medium, high) for factorial design compatibility. Data validation was carried out through consistency checks at both intra-source and inter-source levels. At the intra-source level, the temporal continuity of accident counts was verified using rolling averages and anomaly detection (Z-score thresholds). At the inter-source level, distributions of harmonized variables were compared via Kolmogorov–Smirnov tests to detect statistically significant divergences among countries. Identified discrepancies were flagged for expert review and, when appropriate, corrected via local reclassification.

The multiple-factor analyses conducted using the repository allowed the identification of patterns and correlations between different factors that contribute to accidents. For example, clustering by job task allowed for the identification of specific tasks that were associated with a higher risk of accidents. Combining causes and types of accidents allowed the identification of specific causes of accidents and the types of accidents that were most commonly associated with each cause.

The repository also allowed the investigation of high orders of correlation between different factors in terms of contrast and effects. This information was used to identify specific factors that were associated with a higher risk of accidents and to develop strategies to prevent them.

Table 2. Example of fused dataset.

Accident Specification	Country	Consequences	Impacts	Year	People Affected	TEU/Year
Fall of Persons	Hong Kong	Trauma	Fatal	1998	3	14,582,000
Caught between objects	India	Explosion	Fatal	2006	2	6,141,148
Cuts and scratches	Japan	Trauma	Fatal	2016	2	20,319,000
Electricity	Italy	Trauma	Fatal	2011	2	8,689,878
Water vehicle incident	USA	Trauma	Fatal	2013	10	44,340,866
Mobile plant rollover	New Zealand	Trauma	Fatal	2018	1	3,327,900

4. Design of Experiment

The complexity of the comparison and the need for verification of sources led to the development of a repository based on the systematic collection of data from the indicated sources, structuring its content so that flexible analyses based on queries and DoE could be implemented to verify correlations and finalize sensitivity analyses [16,56].

Once the objective function, represented by accidents, fatalities, and/or injuries, was fixed, the system allowed the data to be extracted and combined, as well as the investigation of higher orders of correlation between different factors in terms of contrasts and effects. For instance, the clustering of job tasks made it possible to combine causes and types of accidents; in this way, accident data could be merged with traffic and macro-parameters related to the respective countries and regions.

The DoE aimed to (i) quantify main effects and interactions among operational, macroeconomic, and contextual factors associated with port accidents; (ii) estimate elasticities of accident rates in response to changes in digitization and traffic; (iii) prioritize risk drivers for training and planning scenarios in M&S/XR simulators. Primary responses were defined as rates normalized by exposure to enable cross-country comparability: accident rate = total accidents/(TEU $\times$ 10^6) per year; severe-injury rate = severe injuries/(TEU $\times$ 10^6) per year; and fatality rate = fatalities/(TEU $\times$ 10^6) per year. When TEU was missing for a country–year, exposure was imputed using interpolation on official port statistics (linear or piecewise cubic, validated through visual diagnostics); sensitivity was reported with and without imputation. The rationale for TEU normalization and the cross-country fusion of archives followed the repository design described earlier.

The factors considered in this study were selected from variables that could be consistently retrieved or reconstructed across the various national archives and external statistical sources included in the repository.

Given the observational nature of the data and the heterogeneity of reporting practices across countries and years, the experimental design was structured as a sequential, multi-stage process.

In the first stage, a screening design was employed to identify the most influential factors and their potential interactions. This was implemented by approximating a resolution IV fractional factorial structure, in which continuous drivers such as digitization, GDP per capita, and traffic intensity were discretized into a limited number of levels (e.g., low, medium, high) and combined with categorical contrasts such as country or regional grouping (East versus West). The aim of this stage was to detect main effects and selected two-factor interactions, such as the interplay between digitization and traffic growth. Because the panel was unbalanced, augmented model-based designs were introduced: missing combinations were reconstructed through nearest-neighbor matching across years and countries, and robustness was assessed by re-estimating results with and without these augmented runs.

In line with the results, this initial screening confirmed that traffic intensity and digitization consistently emerged as the most significant predictors of accident and injury rates across countries, while GDP per capita showed weaker and more variable effects.

Once the main drivers were identified, the second stage refined the analysis through response surface methodology. Continuous factors were retained in their original form and modeled with quadratic and interaction terms, following a central composite structure adapted to the available ranges of the data. This allowed for the detection of curvature effects and provided a basis for scenario analyses that explored marginal "what-if" shifts, for instance, evaluating how a half-standard-deviation increase in digitization could reduce accident rates under constant traffic conditions. Country effects were treated as blocking factors to capture structural differences that may influence baseline risks.

The application of this approach revealed nonlinear effects, particularly in the relationship between digitization and accident rates, where improvements were associated with reductions in accidents up to a threshold, after which the marginal benefits tended to diminish.

Finally, the confirmatory stage embedded the previous findings into a mixed-effects modeling framework. This stage used generalized linear mixed models for count data, with exposure adjusted through TEU as an offset, and included random intercepts for countries as well as random slopes for temporal trends. By incorporating both fixed and random effects, this design accounted for unobserved heterogeneity and repeated measures over time, while simultaneously allowing the estimation of factor sensitivities. Block effects were also introduced to reflect the archive or source of the data, thereby controlling for potential differences in coding and reporting practices.

Through this confirmatory stage, the robustness of the findings was validated: digitization and traffic retained their role as primary drivers, while the influence of job-task composition and impact categories was found to be secondary but non-negligible, especially in explaining variation in severe-injury cases.

Together, these stages created a coherent design structure that progressed from exploratory screening to refinement and confirmatory modeling, ensuring that the analysis was both systematic and robust despite the inherent limitations of observational safety data.

5. Results and Discussion

This section presents the results of the comparative analysis of accident records and discusses the implications of observed patterns in relation to port safety conditions, operational contexts, and socio-economic factors.

5.1. Screening Analysis

The number of accidents by year was compared, considering both fatal and non-fatal accidents extracted by the framework developed. The comparison considered ports of Hong Kong, Japan, Italy, and India. Figures 3 and 4 below report the trends of the countries. Data from Hong Kong and India are available starting from 1997, while for Italy and Japan the national databases make available only the values relating to the last few years. Hong Kong and India show decreasing trends over the years. Italy and Japan, instead, do not show downward trends in the available years. Figure 5 illustrates the relationship between container throughput and recorded fatalities for the countries included in the study over the 1997–2021 period. The ratio—expressed as the number of transported TEUs per one registered fatality—provides a normalized measure of safety efficiency across port systems with different traffic volumes.

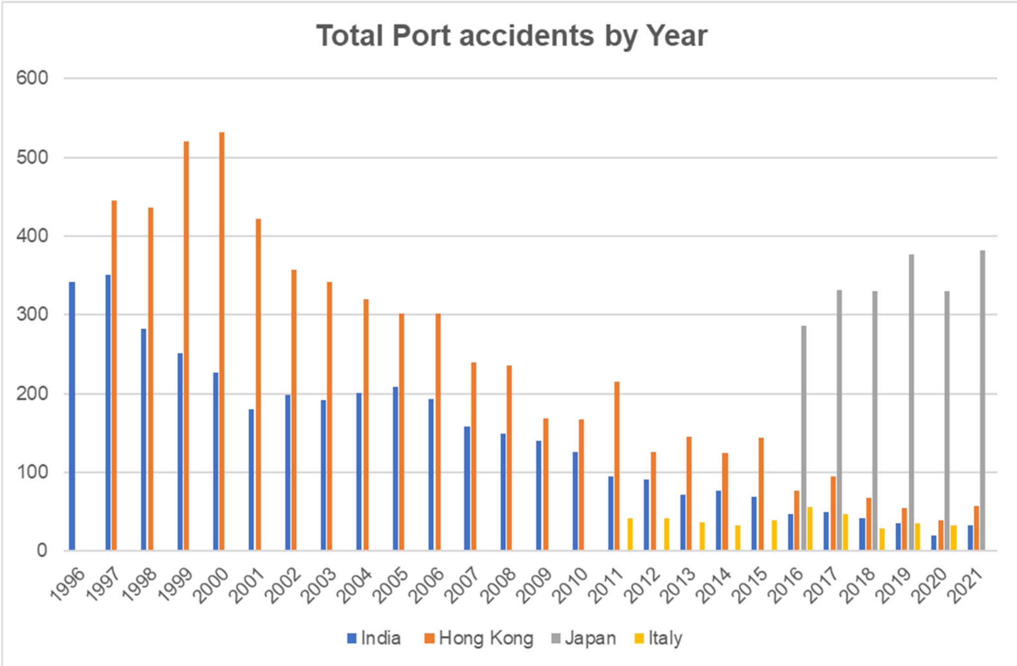

Figure 3. Total port accidents by year for India, Hong Kong, Japan, and Italy.

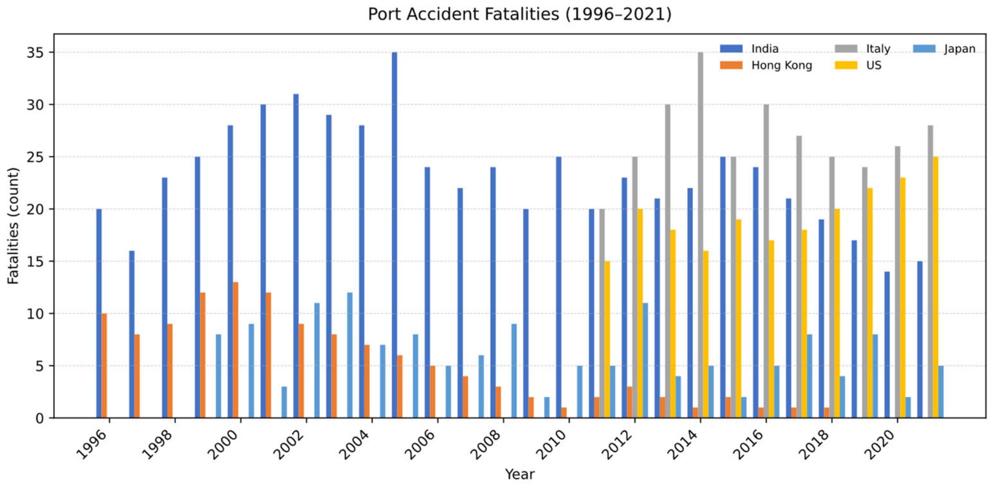

Figure 4. Total number of fatalities by year.

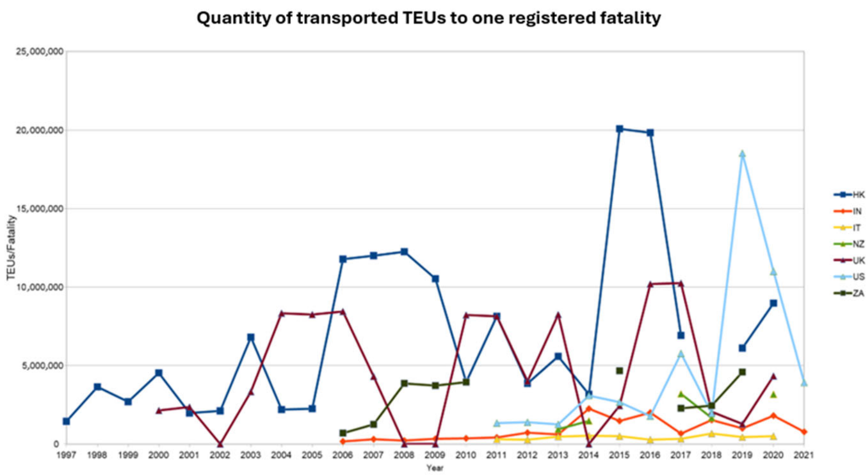

Figure 5. Quantity of transported TEUs per one registered fatality across selected countries (1997–2021).

A further comparison was made considering fatalities and port traffic, measured by TEUs, in each year. The ratio obtained considers the average of TEUs between each mortal accident. The ratio is therefore normalized between each country, considering the effective traffic and not the absolute value of fatalities, which cannot be comparable between different countries. The results are shown below.

5.2. Quantification of Main Effects and Interactions

As for port traffic, other indicators were used in order to find correlations. In particular, socio-economic index ratios were investigated in order to investigate the possible influence of general factors and population factors. These ratios included levels of literacy, average wealth, and familiarity with technologies during different years.

In Table 3 below are reported results considering accidents ratios with two socio-economic parameters: the level of digitization and the GDP per capita. The data reported include those from Hong Kong, India, Italy, and the United Kingdom. The correlation was conducted between the historical series of countries, using the Spearman index, which is reported in Table 3 for all cases. Despite the fact that we do not have homogeneous data, the resulting correlations show general influence on accidents. In particular, digital evolution and overall wealth seem to be linked to the number of accidents. This may be possible due to increasing attention on occupational safety, employment of technological solutions, and a better awareness of working environments and equipment (through training).

Table 3. Correlation between specific parameters and numbers of accidents (fatal/severe) normalized by traffic volume.

Parameter	Accident Type	Hong Kong	India	Italy	United Kingdom
Digitization	Severe	−91.33%	−96.77%	13.46%	−76.59%
	Fatal	−55.41%	−90.11%	41.19%	−19.46%
GDP	Severe	−81.54%	−95.35%	−40.88%	−56.20%
	Fatal	−55.30%	−84.81%	−67.47%	−17.99%

As can be observed in Table 3, the Spearman indexes show inverse correlation trends between categories. Considering digitization, the reported Spearman values suggest a sensible inverse correlation for Hong Kong and India, even if this correlation is not true for Italy. The United Kingdom shows a more relevant correlation considering severe cases and a less relevant one considering fatal accidents. Considering GDP, a negative trend is found for all reported countries, even if there are variations such as in the case of United kingdom.

5.3. Multifactorial Analysis

In order to investigate possible interconnections among the variables related to "port safety," multifactorial analyses conducted were mainly oriented toward testing sensitive parameters. Figure 6 reports the sensitivity analysis involving India and Hong Kong and the relationship between relevant variables considered. All values in figure are normalized and reported on a logarithmic scale.

As can be seen in Figure 6, the analysis showed effects from categories considered, such as incident type and impact. The intercorrelation between factors is important, considering, for example, incident type and impact at the same time. The country factor is present but is limited compared to the other factors when considered alone. Figure 7 below reports a more detailed analysis of different categories considered alone.

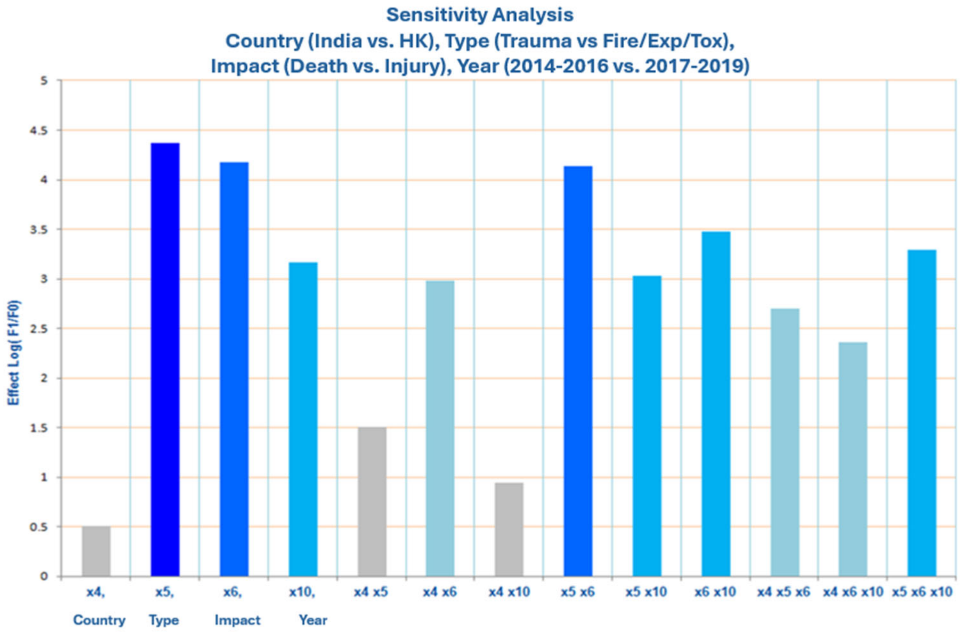

Figure 6. Sensitivity analysis comparing the main effects of country, incident type, impact, and years (2014–2019). The $\log(F/F_0)$ scale indicates relative effect strength.

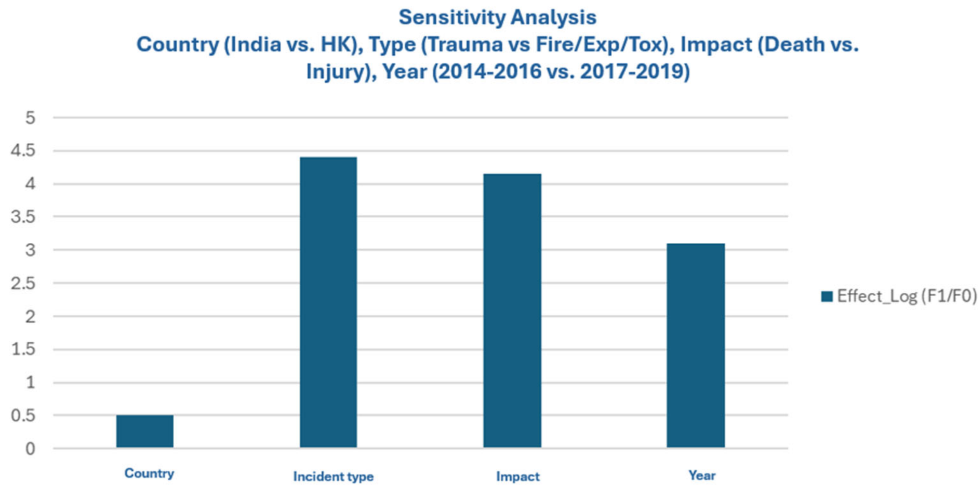

Figure 7. Extended sensitivity matrix illustrating higher-order interactions among key variables: country (x_4), incident type (x_5), impact (x_6), and years (x_{10}).

The comparative analysis focuses on five countries for which sufficient longitudinal data are available: Hong Kong, India, Italy, Japan, and the United States. These datasets vary in time coverage, with Hong Kong and India providing multi-decade records and the other countries offering shorter reporting windows. Despite these differences, all archives were harmonized and analyzed under a unified structure to ensure comparability. As shown in Figure 3, both Hong Kong and India display clear downward trends in total accident and fatality rates over the observed periods. This improvement corresponds to major policy reforms and the gradual introduction of digital safety management systems. In contrast, Italy and Japan do not exhibit significant downward trajectories within the available time windows, indicating either stagnation in safety performance or insufficient temporal coverage to detect long-term improvements. The United States dataset, which covers a comparable time horizon, shows moderate declines in both accident frequency and severity, particularly after 2010, when enhanced reporting standards were adopted.

When accident and fatality counts are normalized by TEU (Figure 4), the relative trends become clearer. Hong Kong and India demonstrate strong improvements in safety efficiency—fewer accidents per unit of traffic—while Italy and Japan show near-constant ratios, suggesting that traffic growth has not been matched by proportional reductions in incidents. The United States exhibits intermediate behavior, with gradual improvement over time.

The Figure 8 shows the relative influence of four variables—type of accident (Falls vs. Vehicles), geographic area (West vs. East), type of impact (Trauma vs. Fires/Explosion/Intoxication), and time period (2014–2016 vs. 2017–2019)—on the observed variation of incidents. The effects are expressed as the logarithmic ratio of F-statistics ($\log(F/F_0)$), indicating each factor's contribution to model variance. The results highlight that *Impact* and *Falls/Accidents* are the most influential factors, followed by *Years*, whereas the *East–West* variable shows a comparatively minor effect.

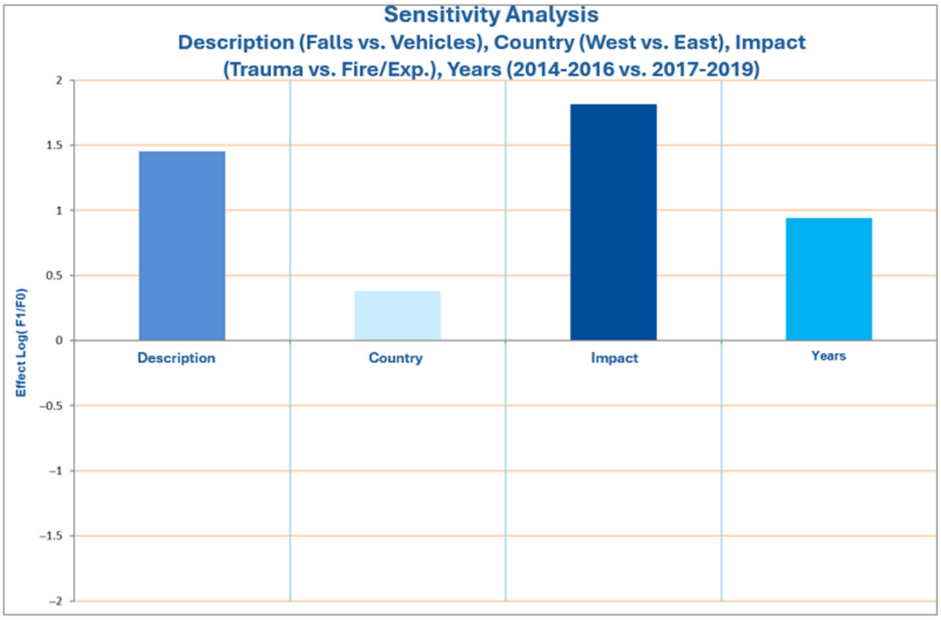

Figure 8. Sensitivity analysis of incident description, country, impact, years.

These results clarify the earlier apparent inconsistency: overall, improvements in safety performance are observed at the global level, driven primarily by the positive evolution in Hong Kong and India, whereas some individual countries, notably Italy and Japan, show no statistically significant downward trends within the available observation period.

5.4. Estimation of Elasticities

Italy is an anomaly in reported transition and sample effects. Unlike other countries, the Italian series shows a weak/atypical correlation between digitization and normalized accident rates. This pattern is consistent with administrative changes in reporting rather than a true worsening in safety outcomes. Italy rolled out telematic tools (Cruscotto Infortuni) with formal usage guidance in 2016 and then introduced a statutory obligation to communicate certain injuries for statistical/informational purposes. In 2025 the system was upgraded to the Registro Infortuni Telematico. Such modernization phases typically raise completeness—capturing events (especially minor/non-fatal ones) that were previously underreported—and thus increasing recorded frequencies during the transition. INAIL's open-data documentation also warns that historical extractions follow distinct logic and should not be over-combined, which can affect apparent trends. Finally, the shorter time horizon available for the Italian port subset amplifies year-to-year variation. Together, these factors offer a parsimonious explanation for the Italian divergence while remaining consistent with the broader finding that digitization is associated with improved safety performance over longer, stable series.

5.5. Final Remarks

Even if the data analysis is not complete, due to difficulties because of limited available datasets, from this study, it emerges that many different correlations and causes can impact port accidents. This is due to nature of port operations, which eventually form a complex system. In particular, analysis conducted on correlation between literacy and wealth suggests that operators' awareness is also important as a guarantee of safety workplace.

Taken together, the results indicate that improvements in port safety are closely linked to the degree to which increases in operational scale are accompanied by modernization in infrastructure, management practices, and workforce preparedness. Countries such as Hong Kong and India display long-term reductions in accident rates when normalized by port traffic, suggesting coordinated progress in regulatory enforcement, technological integration, and training systems. Conversely, the data from Italy and Japan, though more limited in temporal coverage, do not yet show a consistent decline in normalized accident rates, indicating that either safety improvements have been more incremental or that reporting practices and institutional monitoring systems may require further strengthening. Normalization by TEU proved crucial in revealing these differences, as raw accident numbers alone can obscure the influence of expanding operations. The correlation analyses further highlight that rising levels of digitization and economic development are generally associated with reductions in accident rates, although this relationship is not uniform across all cases. In highly developed contexts, the maturity of safety systems appears to depend not only on economic investment but also on organizational culture, adherence to procedural standards, and structured approaches to workforce training. Therefore, improvements in safety outcomes cannot be attributed solely to technological or economic growth; rather, they emerge from the interaction of material systems, regulatory frameworks, and human factors. The multifactor sensitivity analyses support the view that port operations constitute a complex socio-technical environment, where the risk of accidents arises from the combination of machinery use, dynamic vehicle movements, cargo handling conditions, and operator behavior. In all analyzed contexts, certain job tasks and incident typologies consistently appear as higher-risk categories, underscoring the importance of targeted safety strategies rather than purely generalized interventions. These findings reinforce the value of immersive training approaches and predictive safety tools capable of representing operational complexity.

In conclusion, the comparative evidence demonstrates that more effective safety improvements occur where accident reporting systems are coherent, digitization supports real-time monitoring and decision-making, and workforce training emphasizes situational awareness and procedural discipline. These elements together create a feedback environment in which lessons from past incidents can be systematically incorporated into practice. Such results directly motivate the development and deployment of M&S and XR systems, which offer controlled, realistic environments for training operators and evaluating decision-making strategies under variable and potentially hazardous conditions. The framework and analyses presented in this study therefore provide not only a clearer understanding of current safety dynamics in ports but also a foundation for the design of next-generation training and planning tools aimed at reducing risk in complex operational systems.

6. M&S and XR for Improving Port Safety and Efficiency

The proposed framework for statistical analysis of accidents supports proper definitions of major criticalities as well as best actions to prevent and mitigate these risks; indeed it is also very useful to define the requirements for innovative simulators devoted to reducing vulnerabilities, damages, and casualties.

Planning and training have emerged as important factors for port operations: the first one is specifically important for decision-makers, while the second is related to operators. Modeling and simulation have emerged in recent years as effective, key enabling technologies to develop new solutions with reference to these aspects, both for training and for decision-making. In particular, simulation allows us to study synthetic environments, in which models from real systems are recreated to conduct experimentations or run training sessions. In fact, simulation allows the recreation of an explosion scenario within a port by computer technologies, which is not possible and convenient to replicable in reality. Simulation, interoperable Simulation and Serious Games (MS2G) allows us to integrate the M&S approach, guaranteeing high fidelity, with the approach proposed from Serious Games related to user engagement, and intuitiveness due to extended reality. In particular, the authors have worked on multiple projects addressing training and planning in ports and complex industrial systems and addressing important aspects dealing with safety and security. Recent studies have demonstrated how machine learning integrated with simulation modeling can enhance the design and optimization of complex industrial and offshore systems [57], reinforcing the potential of similar approaches for port safety and efficiency improvement.

To define requirements to create models and simulators able to train operators for safety in ports as well as to define the impact of accidents in planning systems for terminals, it is suggested to develop the innovative dynamic framework presented here. This will allow us to identify priorities as well as occurrences of different kinds of accidents within different operations and to refine the requirements and scenarios used by our simulator. The following two projects are proposed as examples; the first project is COYOTE, which supports training of operators in container terminal yards for reducing risks. Indeed, the purpose of this solution is to develop a Serious Game for port operator training in order to prevent accidents. In this case, the player is immersed in a three-dimensional environment, representing the yard of a terminal while vehicles, containers, and cranes are simulated in order to recreate the real system; intelligent agents drive all these components to propose a realistic operation environment. The player is represented by a virtual avatar that has tasks to be completed that require moving and operating inside the port while being exposed to potential risks. Elements of disturbance, such as poor visual conditions, crossing vehicles, noise, etc., are incorporated in the gameplay, making the exercise more challenging as the difficulty level increases. In fact, the player is expected to learn how to avoid dangerous conditions, improving awareness of risks and preventing exposure to them when possible. COYOTE is enabled to operate over multiple platforms that allow us to adopt extended reality (XR) such as Smart Phones, Laptops, HMDs (Head-Mounted Displays), and Augmented Reality Glasses; this allows us to carry out experimentations as well as training sessions in easy way, using different devices selected for the specific goals of these experiences.

Another project that has the opportunity to benefit from this analysis is ALACRES2: a project developed to support decision-makers in defining port plans to face major disasters and accidents. This simulator recreates the dynamics of a disaster, including chemical–physical event behavior, as well as the entities to be used to mitigate the crisis and the potential victims; these elements are directed by intelligent agents and evolve within a three-dimensional environment reproducing a real seaport in which all major port operations are settled. In this scenario, the player defines the specific crisis scenario to be studied (e.g., toxic gas spill, collision between ships with explosions, on-shore tank fires and explosions, etc.). The decision-makers can evaluate alternative plans to manage the accident. Like in strategic video games, the player decides what course of action is more convenient to choose based on available information and assigns tasks to different virtual units, such as fire fighter boats, tugs, recovery vehicles, and helicopters. This simulator is devoted to supporting decision-makers, allowing them to test different alternatives and plans in crisis scenarios. In fact, this simulation uses Monte Carlo approaches to consider the influence of stochastic factors in order to carry out multiple runs and evaluate risks, robustness, and efficiency. In this way, the users are able to develop virtual experience of a crisis and to finalize the most convenient contingency plans as well as to learn how to manage unexpected events following a crisis. The proposed framework allows the definition of the requirements for these simulators by identifying most common and critical accidents.

The analytical findings obtained from the DoE framework directly inform the development of operational and training scenarios within the COYOTE and ALACRES^2 simulators.

In particular, the sensitivity analysis highlighted three dominant factors influencing accident occurrence: (1) incident type, especially trauma- and collision-related events; (2) impact category, with high variability in fire, explosion, and toxic-release incidents; (3) interaction between digitization and operational load, which modulates accident frequency under varying traffic conditions.

These insights are used to parameterize the scenario generation module in COYOTE, where immersive simulations replicate realistic accident chains observed in port terminals—such as crane collisions, hazardous material handling failures, and confined-space incidents. Each scenario integrates contextual variables (traffic intensity, environmental conditions, and workforce digital readiness) corresponding to the statistically significant predictors identified in the DoE.

Similarly, in ALACRES^2, which focuses on mitigating disasters in maritime and port areas through the use of modeling and simulation, the task models and evaluation metrics are derived from the same analytical dataset. Accident typologies with high sensitivity coefficients are translated into training modules emphasizing situational awareness, procedural compliance, and operator workload management. Performance indicators such as reaction time under alarm, decision latency, and error probability under cognitive stress are selected to correspond to the risk dimensions quantified in the DoE results.

7. Conclusions

This study examines port safety conditions using a comparative framework that integrates accident data from multiple national archives, harmonizes heterogeneous classification systems, and applies DoE techniques to identify factors influencing accident rates. The results show that when accident data are normalized by port traffic volume, the long-term trends differ substantially across countries. Hong Kong and India exhibit a steady improvement in safety performance over time, while Italy and Japan, for which only partial historical records are available, show more variable trends. This finding confirms that assessing safety performance requires exposure-based indicators rather than raw accident counts.

The correlation and multifactor analyses further indicate that improvements in safety outcomes are associated with increases in digitization levels, economic development, and the presence of structured safety management systems. However, the relationship is not uniform across countries, suggesting that cultural, organizational, and regulatory factors also play significant roles. Additionally, certain categories of port activities—particularly those involving heavy machinery and dynamic cargo handling—consistently present higher risks, reinforcing the need for targeted rather than generalized safety interventions.

While the proposed framework provides a scalable approach for comparing port safety conditions across regions, this study has several limitations. The availability and granularity of accident data vary considerably between countries, and reporting practices are not always harmonized. In some cases, only severe or fatal events are recorded, preventing analysis of near misses or minor incidents that could reveal important precursors to major accidents. Furthermore, digitization and socio-economic indicators were used as proxies for safety maturity, but more direct measures of risk governance, training quality, or technological deployment would improve the robustness of the analysis.

Future research should therefore focus on expanding the dataset to include additional countries and longer time horizons, incorporating near-miss and incident precursor data where available, and validating the proposed framework through collaborations with port authorities. Moreover, the results should be operationalized within M&S and XR environments, enabling the development of scenario-based training modules that reflect the most critical accident pathways identified in this study. Such simulation-based safety tools have the potential to support both real-time decision-making and long-term improvements in operator awareness and risk management.

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