An integrated analysis of key factors causing fires in high-tier containers on Ultra-Large Container Vessels

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المستخلص
يهدف هذا البحث إلى تحديد العوامل المنطقية الكامنة وراء العامل البشري، ونقص التصريح عن البضائع الخطرة، وغياب نظام متطور للكشف عن الحرائق، وهي الأسباب الرئيسية لاندلاع الحرائق في الحاويات المخزنة في الطبقات العليا على سفن الحاويات العملاقة، بالإضافة إلى استكشاف الحلول المحتملة مثل الوقاية من الحرائق والتخفيف من حدتها؛ وقد استخدم الباحث الأساليب الوصفية التحليلية وطوّر استبيانًا وُزّع على البحارة، حيث تأهلت ١٥٦ استجابة للمعالجة باستخدام برنامج SPSS الإصدار v٢٦، وقد أبرزت النتائج أن أكثر العوامل تأثيرًا كانت العوامل البشرية، والبنية التحتية للكشف عن الحرائق، وعدم الإعلان البضائع الخطرة ، وبناءً عليه، يوصي البحث بضرورة توفير أنظمة أكثر تطوراً للوقاية من الحرائق، وتنفيذ لوائح وقوانين أكثر صرامة بشأن البضائع المعرضة لخطر الحريق، وتطبيق تدريب للتخفيف من مخاطر الحريق على طاقم السفينة، ويُعمم هذا العمل لمشغلي السفن والجهات التنظيمية وأصحاب المصلحة في قطاع النقل البحري لتعزيز ممارسات السلامة وحماية الأرواح والبضائع والبيئة البحرية.

Abstract
The purpose of this research is to determine the reasoning behind the human factor, the lack of declaration of dangerous goods, the lack of a sophisticated fire detection system, the primary causes of fire outbreaks on high-tier stowed containers on Ultra Large container vessels (ULCVs), and potential answers: fire prevention and fire mitigation. The researcher employed descriptive-analytical techniques and developed a survey distributed to seafarers. 156 responses qualified. They were processed using SPSS v26. The researcher brought to light the most impactful of which were human factors, fire detecting infrastructure, and lack of declared dangerous cargo. It is recommended in this research that more sophisticated fire prevention systems should be in place, more stringent regulations on fire-hazardous cargo should be implemented, and that fire risk mitigation training should be implemented on the part of the crew. This research is disseminated to ship operators, the fire safety practices regulatory and stakeholders in the maritime transport sector to enhance fire safety practices and protect life, cargo, and the marine environment.

Keywords: Ultra Large Container Vessels (ULCVs) – Container Fire Safety - Human Error - Undeclared Dangerous Goods - Fire Detection Technology - Marine Accidents

1. Introduction

Maritime transport is the backbone of trade and the core of the global economy by contributing to the transfer of intercontinental trade, as it represents the transportation of raw materials, foodstuffs, and manufactured goods, with more than 80% of the products being transported around the world, and 70% of the global trade value is transported by ships of all types (Salihoglu and Beşikçi, 2021). Around 60 thousand merchant vessels of various types and sizes are roaming the world to transport all kinds of goods (Deggim, 2021). Due to the industry's sheer scale and its vital role in supporting international commerce, considerable attention has been directed by global maritime bodies toward the challenges it encounters. In particular, the issues of safety of navigation and protection of the marine environment drew the attention of scholars and led to the continued development of global regulations and international cooperation at different levels (Helal, 2021).

There have been changes in the design and size of container ships within the last 10 years. The larger the ships get and the more cargo they can hold, the greater the concentration of boxes on a limited number of vessels. This concentration increases the likelihood of container fires and explosions, resulting in catastrophic losses (Krmek et al, 2022). The safety of the entire marine transport system is jeopardized due to fires on vessels, as assets, cargo, and lives can be lost, and there is pollution of the ecosystem (Luo and Shin, 2019). The losses, especially the ones that stem from ship fires, are devastating in many aspects, including the safety of the crew, the ecosystem, and the financial and social image losses for the shipping line (Avazov et al, 2023).

As noted in the Safety and Shipping Review (2023), fires were the second leading cause of complete loss of a vessel for the year prior, contributing to 18% of the total value of the analyzed insurance claims.

The last decade has seen a reduction in total losses of shipping because of advances in technology and better training of crews. However, fires have not seen a corresponding reduction. The year 2022 recorded 209 incidents of fire, the highest in the last 10 years. One such fire was in January of 2022, when a vessel carrying over four thousand luxury brands, such as Porsche, Audi, Bentley, and Lamborghini, caught fire in the Mid-Atlantic, and two firefighters lost their lives, contributing to the total loss of 438 million USD (Zhang et al., 2024). Fires also rank second in terms of causes of maritime insurance claims, amounting to 18% of all claims, in both number and amount (Wang et al., 2021).

Figure (1) illustrates the number of container fire casualties. It has been noticed that the number of container fire casualties in 2019 was 31 fire accidents, which dropped to 25 accidents in 2020 before rising again to 36 in 2021 (Metwalli, 2022), revealing the importance of identifying root causes behind those rates in general and identifying solutions for future prevention.

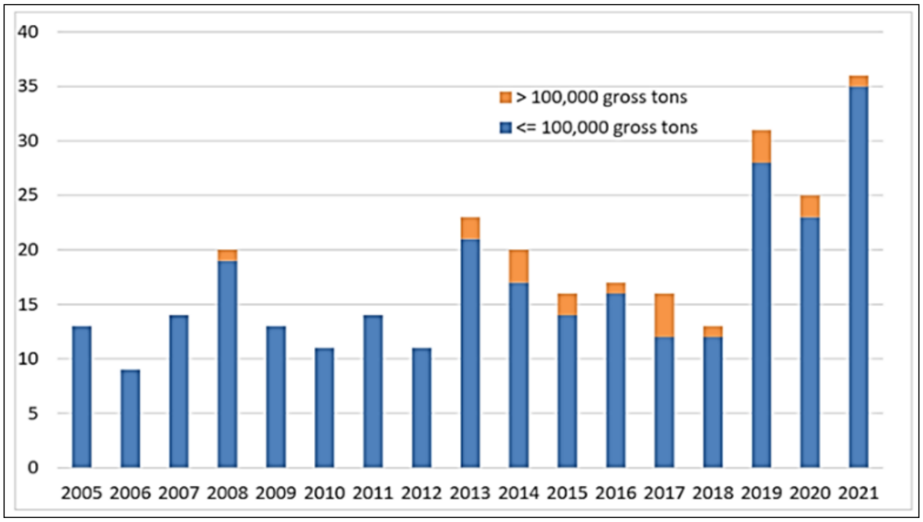

Figure (1) : Container vessel fires- occurrence per year (Metwalli, 2022)

Considering the evidence, the central problem dealt with in this research is that the risk of fire on vessels is ever-present, even with the advent of modern technologies and additional safety regulations. The issue is exaggerated with the size and capacity of ultra-large container vessels (ULCVs). These vessels continue to adhere to the same safety design principles and neglect the evolving nature of fire-related hazards and the safety and protection of the crew. The literature, however, is focused on the traditional aspects, such as human error and explosions onboard however, are emerging and possessing high importance. Insufficient fire-detecting and fire-monitoring systems declared and/or undeclared dangerous goods stowed onboard, and the fire risks due to the stacking of containers are overlooked. The study is meant to address the interaction of these aspects in determining the probability and magnitude of the fire on ULCVs to improve understanding and assist in formulating efficient preventive and protective measures and policies in the field of maritime transport.

2. Literature Review

2.1 Growth and Challenges of ULCVs

Over the last 25 years, the global container shipping industry has seen an increase in the average ship size. This trend in the construction of ultra-large container vessels has been tied to the pursuit of economies of scale in the industry, as larger ships yield lower costs per TEU transported (Ge et al., 2021; Jungen et al., 2021). Between 2011 and 2021, global container capacity grew by more than 65%; however, the number of vessels in the industry grew only about 9%. This suggests that growth in the container shipping industry results from increasing vessel size rather than adding more vessels (Callesen et al., 2021). The work of Stopford (2009) and Sys (2009) indicates that economies of scale have thresholds, with estimates being around 7500 TEUs. This is because several operational challenges, such as ship efficiency, cost management, and safety issues, arise as vessel size continues to grow (El Adl Ibrahim El Adl & Alamoush, 2026).

The capacity increases of ULCVs, first reported in 2020, as capable of carrying over 23,000 TEUs, have led to changes in port operations and navigation. 2020 has long been noted as a starting point of the pandemic, and the increased capacity of vessels has correlated with the increased flow of globalized trade and the resultant bottlenecks. These include; the depth of the port, the outreach of the cranes, the capacity of the port to handle yard, and pilot training. These vessels impose a greater environmental and structural burden on port systems, leading to trade-offs in project costs and diseconomies of scale and efficiency (Aboud & Badry, 2023).

The cost and environmental burden of keeping these vessels economically operational exerts pressure on port systems to forgo efficiency in the beam and to dig deeper drafts to lessen the trade-offs from the above efficiencies. The increases have a marked cost for the surrounding ecosystems.

2.2 Fire Risks and Incident Patterns Onboard Ships

Fires continue to be one of the top dangers to safety at sea. The operational environment on a ship has many possible fire ignitions sources, including the fuel systems, electrical circuits, combustible cargo, and sealed working spaces, all of which create a fire prone environment (The Nautical Institute, 2023); The severity of the situation can be understood from the historical incident data, fires and explosions represented about 19% of bulk carrier incidents from 1980 to 2010 (Roberts and Marlow, 2005), and almost 10% of all maritime losses from 2006 to 2015 (Allianz Global Corporate & Specialty, 2016).

Fires on ships, like other types of accidents, usually develop rapidly and leave little time for evacuation and emergency actions, which results in higher fatalities (Shichuan et al., 2012). Ship fires, especially those containing hazardous or chemically reactive cargo, can also have serious environmental consequences (Baalisampang et al., 2018). The enormous number of damages resulting from fires at sea is also a result of underreporting, which is a common problem in maritime safety data (Hassel et al., 2011).

2.3 Major Causes of Maritime Fires and Explosions

2.3.1 Human Error

Based on ABS (2003) statistics, Baker and McCafferty (2005) argue that there is no disputing that human mistakes made at sea are the leading cause of marine accidents, consisting of approximately 80 to 85% of the documented cases in accident reports across different jurisdictions. Under-reporting errors result from several factors, such as fatigue, lack of proper training, and failure to follow established operational guidelines (Wagenaar and Groeneweg, 2005). Reason (2000) arranges such errors into the two categories of ‘active failures’ (unsafe acts by crew) and ‘latent failures’ (systematic deficiencies in organization, i.e., policies, training, or provision of ineffective tools).

According to Apostol-Mates and Barbu (2016) and Class (2010), such deficiencies do not occur in a vacuum, as they argue that such combinations of errors demonstrate the relationship between the human factor and the organizational safety culture of the maritime system.

2.3.2 Mechanical Failure

Mechanical problems are also a significant source of fires at sea. As noted by Darbra and Casal (2004), mechanical failure is the second most frequent type of accident reported across the maritime sector. Earlier studies indicate that roughly one-third of incidents involving hazardous materials stem from issues such as worn-out components, harsh operating environments, or faults in safety systems (Vilchez et al., 1995; Bejger and Drzewieniecki, 2015). The Allianz report (2016) likewise shows that mechanical breakdowns were responsible for a notable share of vessel losses between 2007 and 2016. In several cases, failures within the firefighting systems themselves, particularly in cargo holds, have triggered severe disasters, as seen in the container vessels MSC Flaminia and Maersk Honam accidents (IUMI, 2023).

2.3.3 Chemical and Thermal Reactions

Self-ignition of dangerous and toxic substances is another noteworthy cause of fire on board vessels. Some estimates suggest that containerized cargo includes hazardous materials in about ten to forty percent of cases (HELCOM, 2002; Munich Re Group, 2002). Dangerous materials that are kept inappropriately or kept in proximity to other, incompatible, chemicals greatly increase the chance of a severe reaction to occurring, as in the case of vessels Hyundai Fortune (2006) and Hanjin Pennsylvania (2002) where a dangerous good such as calcium hypochlorite, as well as the highly flammable, magnesium, some of which was undeclared or mis-declared, substantially contributed to the explosions and subsequent fires (ATSB, 2007; Ellis, 2010).

2.3.4 Electrical Faults

Fires caused by electricity continue to be a major threat, mainly due to faulty connections, overloaded systems, or poor-quality setups (Jadin & Taib, 2012). Studies show that between 50 to 70% of all recorded cases of electrical fires and incidents involve electrical distribution and illumination systems (Babrauskas, 2008; Campbell, 2017). Some overarching causes may be the lack of replacement of aged-out systems, a destructive (as in faulty) modification of the systems, or a complete lack or neglect of the maintenance of systems (McCoskrie, 1990; Baalisampang et al., 2018).

2.4 Fire Identification and Detection Approaches

Conventional methods for detecting fires, such as manual checks, smoke-based alarms, and standard sensor systems, come with notable shortcomings. Human inspection can be inconsistent and prone to fatigue, while sensor networks often have limited coverage and require significant upkeep. Advances in thermal imaging and Computational Fluid Dynamics (CFD) modelling show that heat-detection systems can identify rising temperatures nearly twice as quickly as traditional detectors, offering better early-warning capability for high-risk container fires (Callesen et al., 2019).

2.5 Fire Incidents on High-Tier Containers and Open Decks

Fires that start in high-tier container stacks on open decks pose a serious threat because access to these areas is limited, and heat can spread quickly from one container to another (Callesen et al., 2019). Many of these incidents are tied to hazardous cargo or smoldering materials that go unnoticed until ignition occurs. Their rising frequency, roughly one event every nine days in 2023, has been linked to the growing size of container ships and the ongoing problem of mis declared cargo (Gard, 2024; Allianz, 2024).

Several mitigation measures have been suggested, including placing heat sensors directly inside containers, using infrared monitoring systems, and adopting technologies such as the HydroPen, which drills through container doors to deliver water straight into the affected unit (ClassNK, 2023; EMSA, 2023). Fires on open decks are further complicated by weather conditions like wind and rain, as well as operational mistakes during cargo handling and failures in mechanical or electrical systems (Sanz et al., 2023; Krmek et al., 2022).

2.6 Impacts of Shipboard Fires

The Safety and Shipping Review (2023) notes that fires accounted for 18% of all maritime insurance claims, making them the most expensive cause of vessel losses. Even with advancements in safety technology, the number of reported fire incidents rose to 209 in 2022, marking the highest figure recorded in ten years. High-profile cases, including the mid-Atlantic fire that destroyed more than 4,000 luxury vehicles in 2022, highlight the substantial economic, environmental, and human consequences that result when fire control measures fall short (Zhang et al., 2024).

2.7 Review of Previous Studies

There has been a recent investigation into detection and firefighting techniques used on ships. Ziyang and Roberts (2024) developed a model that uses real-time Ship-Fire Net detection based on YOLOv8n that has a precision and recall of 0.93. Working along similar lines, Sanz et al. (2023) analyzed the risk of ultra-large container vessels subjected to extreme environmental loads and proposed the use of synthetic lines and intelligent mooring systems to cut the risks associated with fire and mooring failures. From the analysis of 19 cargo fire incidents (2010-2020) based on the HFACS-CSCF framework, Metwalli (2022) stated that fire outbreaks can be linked primarily to undeclared dangerous goods. That same concern was stated earlier by Krmek et al. (2021), who claimed that existing firefighting means on container ships do not meet the demands of the situation and urged the need for drastic changes to the framework and technology. Callesen et al. (2021) analyzed and suggested changes to the CFD model to detect early fire and smoke, composed of calcium hypochlorite, compressed charcoal, batteries, and divinylbenzene, that are high-risk cargo. There are findings stemming from these, along the lines of Baalisampang et al. (2018) performed a scale meta-analysis on fire and explosion incidents for the period 1990–2015 and emphasized the alternative fuels, including LNG and methanol, potentially being able to mitigate fire risks within the maritime domain.

3. Identified Research Gaps

There will be a lot more research on fire safety. However, a few things will still be left unfinished. Many works will neglect the unique risks that come with the stowage of larger containers on ULCVs. Many more works will attempt, but simply fail, to create comprehensive risk assessment models that fully incorporate the role of human error, undeclared hazardous cargo, and limitations of detection technologies. Because of a lack of documented fire incidents, there will be a lack of operational evidence to improve systems. Given everything described, this research will focus on overlooked factors to improve safety systems operationalized through data that will be targeted to the reduction of fire incidents and the factors that contribute to fire incidents and their consequences on ULCVs.

4. Research Design and Methodology

This study adopts a quantitative research methodology designed to analyze the relationship between human error, undeclared dangerous goods, and the absence of fire detection technologies, and their impact on fire occurrences in high-tier containers on ULCVs.

The main research tool was a structured questionnaire developed based on previous literature and expert consultation. It consisted of 46 statements distributed across four constructs: Human Error (13 items), Dangerous Goods (11 items), Fire Detection Technology (9 items), and Fire Risks (13 items).

The answers were evaluated based on a five-point Likert scale with values of “Strongly Disagree” (1) to “Strongly Agree” (5). Both content and face validity stem from the pilot study that helped adjust wording and relevance of the items.

The study population consisted of deck officers and marine engineers with experience in operations aboard ULCVs. Using simple random sampling, 156 valid responses were gathered electronically using Google Forms. This response rate surpassed the minimum size needed to ensure statistical power for the regression analysis (15 responses for each variable), which preserved the representativeness and the analytical depth as well (Helal, 2021).

The primary source of data was the questionnaires for the primary dataset, while the secondary dataset was derived from academic journals and technical papers. Using the Statistical Package for Social Sciences (SPSS V26), data were subjected to analysis, which consisted of both descriptive measures of descriptions and inferential statistics based on a significance value of 0.05. To check the validity of the questionnaire, a test for internal consistency for each of the items was done using Pearson’s correlation coefficient. Reliability, on the other hand, was determined using Cronbach’s alpha, where values of 0.70 and above were accepted as good indicators of internal consistency.

5. Hypotheses Test

5.1 First Hypothesis

H1: *Human error has a significant impact on ULCVs cargo fire occurrence.* To test this hypothesis, a multiple regression analysis was applied to assess the influence of the three dimensions of human error, physical and psychological conditions, compliance and organizational errors, and decision-making and judgment errors on ULCVs cargo fire occurrence.

Table 2 presents regression results.

Table (2) Multiple Regression Analysis of Human Error on Container Ship Cargo Fires Occurrence.

Model	Unstandardized Coefficients		Standardized Coefficients	t	Sig.	ANOVA Sig
	B	Std. Error	Beta			
(Constant)	.726	.157		4.613	.000	0.000
physical and psychological conditions for ship staff	.270	.082	.290	3.280	.001	R^2 = 0.780
Compliance and Organizational Errors	.300	.092	.321	3.274	.001	
Decision-Making and Judgement Errors	.284	.095	.306	2.994	.003	

The **ANOVA significance value (Sig = 0.000)** confirms the overall model significance at the 0.05 level. All three predictors had **positive and statistically significant effects**:

- Physical and psychological conditions (B = 0.270, t = 3.280, p = 0.001)
- Compliance and organizational errors (B = 0.300, t = 3.274, p = 0.001)
- Decision-making and judgment errors (B = 0.284, t = 2.994, p = 0.003)

The R^2 value of 0.780 shows that human error dimensions account for 78 % of the variation in cargo fire incidents, which reflects a strong level of explanatory power within the model. Based on this result, H1 is confirmed, indicating that human error has a considerable influence on the occurrence of fires aboard ULCVs.

5.2 Second Hypothesis

H2: *Undeclared dangerous goods have an impact on ULCVs cargo fire occurrence.* A multiple regression analysis was conducted to measure the impact of handling stowage errors and declaration of errors on fire incidents.

Table (3) Multiple Regression Analysis of Undeclared Dangerous Goods on ULCVs cargo fire occurrence

Model	Unstandardized Coefficients		Standardized Coefficients	T	Sig.	ANOVA Sig
	B	Std. Error	Beta			
(Constant)	.667	.154		4.335	.000	0.000
Handling and Stowage Errors	.410	.108	.437	3.806	.000	**R^2** = 0.791
Documentation and Declaration Errors	.436	.108	.464	4.041	.000	

The ANOVA significance value (0.000) verifies the model's validity, with $R^2 = 0.791$, meaning 79.1% of fire occurrence variance is explained by the predictors. Both factors have statistical significance:

- Handling and stowage errors ($B = 0.410$, $\beta = 0.437$, $t = 3.806$, $p < 0.001$)
- Documentation and declaration errors ($B = 0.436$, $\beta = 0.464$, $t = 4.041$, $p < 0.001$)

These results confirm that mishandled or undeclared hazardous goods are major contributors to cargo fires. Accordingly, the second hypothesis is accepted, with the need for stricter control and accurate declaration of dangerous cargoes.

5.3 Third Hypothesis

H3: *Fire Detection Technology has an impact on ULCVs cargo fire occurrence.*

A simple regression analysis was performed to examine the relationship between fire detection technology and fire incidents.

Table 4 shows that the model is highly significant (**ANOVA Sig = 0.000**), with **R^2 = 0.836**, indicating that 83.6% of the variation in fire occurrence is explained by detection of technology efficiency. The regression coefficient ($B = 0.873$, $\beta = 0.915$, $t = 28.155$, $p < 0.001$) confirms a strong positive impact.

Table (4) Simple Regression Analysis of Fire Detection Technology on ULCVs cargo fire occurrence

Model	Unstandardized Coefficients		Standardized Coefficients	t	Sig.	R	R^2	ANOVA Sig
	B	Std. Error	Beta					
(Constant)	.619	.133		4.640	.000	.915	.836	.000
Fire Detection Technology	.873	.031	.915	28.155	.000			

Accordingly, the third hypothesis is supported that advanced fire detection technology reduces the likelihood of cargo fires, which may enhance maritime safety.

6. Recommendations

- Improvement of the human element of the organization will require the development of a holistic approach to psychological support, ongoing safety training, plus the application of modern systems for the detection, assessment, and control of errors in the system before they occur.
- Strengthening the mechanisms put in place for the declaration of cargo and the subsequent handling of the cargo should include the adoption of stringent regulatory frameworks, supported by AI-powered inspection systems and real-time control systems to detect and classify hazardous materials that are either undeclared or improperly declared.
- There should be a commitment to the adoption of advanced technologies for the detection and prevention of fires, which should include automated systems for the activation of alarms, systems for the capture of images along a thermal spectrum, and smart containers that are designed to monitor their internal status.
- Expanded development of experiential learning and competence training is possible for the crew through structured, systematic approaches to mentoring and simulation, which are sufficiently realistic to improve situational awareness and the competency of emergency response management systems.
- Updating international maritime regulatory instruments, particularly the Safety of Life at Sea (SOLAS) Convention and the International Maritime and Dangerous Goods (IMDG) Code, should incorporate a requirement for the electronic verification of cargo. It should also tie vessel certification to the installation, verification, and periodic testing of an advanced, tiered fire detection and suppression system.

7. Conclusion

This study addressed the reasons for viable solutions to the occurrence of fires in high-tier containers of (ULCVs). The data indicated that the human factor, the presence of undeclared dangerous cargo, and not having sufficient fire detection systems are the main causes that affect the occurrence and severity of the fire in the containers. Out of the stated variables, the human factor, especially poor decision-making, fatigue, and compliance with procedures, was the most significant reporting in nearly 78% of the cases. Furthermore, the study also indicated that improper handling and undeclared dangerous goods increase fire risk, and the absence of fire detection systems.

The new integrated safety management techniques with real-time monitoring and human factor engineering focus will be needed, according to the results. Utilization of AI-assisted real-time monitoring of containers, thermal imaging systems, and smart containers can bolster the early warning and response to fire threats to a great extent. At the same time, the SOLAS Convention and the IMDG Code must be updated to incorporate additional electronic cargo manifest requirements, fire detection and suppression systems at various locations, and fire detection and suppression systems to contain operational and fire safety threats.

Also, this assists ship operators, classing societies, and regulators in working with new documentation and evidence on maritime safety. The fire loss in maritime safety and shipping can be made safer, and the loss of fire can be safer and more sustainable shipping to the world.

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