An Analysis of Operational Approaches to Dangerous Goods Container Storage in Ports and a Study on Turkish Container Ports*

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Abstract: The escalating transportation of hazardous materials by sea necessitates a more systematic and comprehensive approach to container storage operations within port areas, particularly in terms of safety and risk management. The present study aims to analyse the operational approaches and prioritisation tendencies of container terminals operating in Türkiye with regard to the storage of dangerous goods containers. A comprehensive review of the extant literature yielded six key criteria associated with storage operations. These criteria, which are outlined below, were identified as being of particular importance: the requirement for an emergency response unit; storage area safety; communication systems; authorised personnel access; dedicated storage areas; and designated operational areas.

In the course of the research project, a structured survey was carried out with the 20 largest container terminals operating in Türkiye. The collected data were analysed using the Analytic Hierarchy Process (AHP), a multi-criteria decision-making method that enables the evaluation of relative importance among criteria. The analyses were conducted utilising the SuperDecisions software, with the relative weights of the criteria being calculated. The findings indicate that the safety of storage areas and the presence of an emergency response unit are of the utmost importance. The collective weight of these two criteria exceeds half of the total, thereby demonstrating that port managements primarily emphasise risk mitigation and crisis response capacity. The study emphasises that dangerous goods storage operations are managed within a holistic safety management framework, rather than solely as logistical activities.

Key Words: Maritime Transportation Engineering, Maritime Management, Dangerous Goods, Storage Operations

1. INTRODUCTION

The fundamental components of maritime transport operations are ships and ports, which ensure the efficient functioning of the supply chain (Arıcan et al., 2022). Ports are considered to be critical infrastructure, facilitating the movement of goods across international borders. Maritime transport is the predominant mode of global trade (Sanchez-Gonzalez et al., 2019). The operational complexity of contemporary ports has increased considerably due to the volume and variety of cargo handled, including substantial quantities of hazardous materials. Despite the digitalisation of maritime transport lagging behind that of other sectors, it is gradually transforming port operations through the integration of autonomous vehicles and robotics, artificial intelligence, big data analytics and the Internet of Things (IoT) (Sanchez-Gonzalez et al., 2019). Maritime operations are a field of activity that requires a high level of responsibility and involves demanding working conditions. The fact that seafaring personnel are required to spend protracted periods at sea and face challenging working conditions highlights the importance of the human factor in operational processes (Arslan, Arıcan, Ünal & Yaramış, 2021). In order to ensure that port operations are carried out in an effective manner, it is necessary to establish the appropriate infrastructure, operational areas and safe working environments (Ünal et al., 2022).

Ports function as pivotal nexuses for the storage, transhipment and transport of dangerous goods, including chemicals, flammable substances, toxic substances and other hazardous materials. Effective communication within dangerous goods storage areas at ports is of the utmost importance for ensuring worker safety, preventing accidents, coordinating emergency responses and maintaining regulatory compliance. The storage of hazardous cargo containers within port facilities represents a critical intersection of logistics, security management and emergency preparedness. Ports function as pivotal nodes in global supply chains, handling substantial volumes of cargo that have the potential to pose significant risks to human health, infrastructure, and the environment. The management of hazardous materials requires specialised knowledge, infrastructure and protocols to ensure safe transport, storage and shipment.

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The management of hazardous cargo containers in port environments constitutes a pivotal operational dilemma, Schnittker et al. (2022) argue, intersecting with maritime safety, environmental protection, occupational health and supply chain management. Ports are considered to be fundamental to infrastructure for economic growth and development, and they function as critical nodes in global trade networks (Azarkamand et al., 2020). However, the concentration of hazardous materials in port environments gives rise to unique risks that demand sophisticated management approaches. While the maritime transport sector constitutes the foundation of global trade, it has confronted substantial challenges concerning digitalisation and security management in comparison to other sectors (Sanchez-Gonzalez et al., 2019). The storage of hazardous cargo in port facilities represents a critical intersection point in terms of maritime logistics, safety engineering and regulatory compliance. Ports function as pivotal nodes in global supply chains, handling a diverse range of cargo types, including materials that present considerable risks to human health, environmental integrity, and infrastructure security (Vero et al., 2019).

The management of dangerous goods in port environments represents a critical intersection of logistics, safety engineering, environmental protection and public health. Ports are considered to be of pivotal significance for the facilitation of economic growth and development, as evidenced by their role in the efficient movement of goods within global supply chains (Azarkamand et al., 2020). However, the storage and transport of hazardous materials within these complex operational environments require specialised operational areas. The purpose of these areas is to minimise risks to workers, local communities and the environment. The reverse logistics of hazardous waste, including municipal hazardous waste, has attracted significant interest from researchers and practitioners due to the significant impact of the safe transport and effective management of hazardous waste on public health and environmental sustainability (Xin et al., 2021).

Hazardous cargo comprises a wide variety of substances that pose risks to human health and safety, and the environment. The characterisation of the physical hazards of cargo is of crucial importance in the provision of information for the management of the risks associated with their use, storage and transport (Fayet and Rotureau, 2020). The classification of hazardous cargo encompasses numerous categories, including flammable substances, corrosive substances, toxic chemicals and biological agents. Each category presents its own unique storage challenges, requiring specific infrastructure and handling protocols. It is vital to analyse the content of storage operations and to prioritise the most critical operations in order to minimise the risk levels associated with the storage of dangerous goods containers in ports.

2. Hazardous Cargo Container Storage Operations at Container Terminals

The secure storage of dangerous goods containers within port areas is intrinsically linked to the digital systems and automation technologies employed in port operations. The utilisation of autonomous and intelligent port applications has been demonstrated to enhance operational efficiency by facilitating the tracking of cargo movements, thereby reducing human error (Ünal and İnegöl, 2024). The storage of dangerous goods in ports is governed by a complex framework of international regulations, including the International Maritime Dangerous Goods (IMDG) Code, the International Ship and Port Facility Security (ISPS) Code, and various environmental conventions. The overarching objective of these regulations is to establish minimum standards for the design of storage facilities, operational procedures, and emergency response capabilities. In order to comply with international standards, a systematic approach is required in relation to the identification of hazards, the assessment of risk and the implementation of controls. The characterisation of the physical hazards of substances provides essential information for managing the risks associated with their use, storage and transport (Vero et al., 2019). It is incumbent upon port authorities to ensure that hazardous cargo storage facilities meet or exceed these standards whilst complying with local conditions and regulatory requirements.

In addition to complying with international standards, ports are also required to adhere to national and local regulations pertaining to the storage of hazardous materials. These may include building regulations, fire safety regulations, environmental permits and occupational health and safety requirements. The integration of these various regulatory requirements into consistent facility design and operational procedures poses a considerable challenge for port authorities. The storage of dangerous goods in ports necessitates a meticulous evaluation of the physical and chemical properties of these substances. The management of hazardous cargo in ports is governed by international conventions and standards that define classification, packaging, labelling and storage requirements. Evidence-based biosafety principles provide frameworks to protect people and the environment from the risks associated with working with hazardous substances (Kimman et al., 2008). Risk assessment, biological containment, concentration, and enclosed spaces are among the principles forming the basis of current biosafety practices (Kimman et al., 2008).

Port workers are exposed to a wide range of occupational health hazards associated with the storage of hazardous cargo. The restructuring of ports that has been necessitated by modernisation efforts has had significant impacts on the health of workers, as well as on workers across various categories involved in operational activities (Maciel et al., 2012). The issue of the storage of hazardous cargo in ports is of particular concern, as it poses potential risks to marine ecosystems through the possibility of accidental releases and chronic contamination.

2.1. Safety of Hazardous Materials Storage Areas

The security of areas where dangerous goods are stored in ports represents a critical intersection in terms of maritime safety, supply chain integrity, environmental protection and national security (Azarkamand et al., 2020). The security of areas where dangerous goods are stored is a multifaceted issue that encompasses numerous dimensions. These include, but are not limited to, physical security measures, access control systems, surveillance technologies, cyber security protocols, emergency response capabilities and regulatory compliance. The characterisation of the physical hazards of substances provides essential information for managing the risks associated with their use, storage and transport (Fayet and Rotureau, 2020). It is imperative that a comprehensive risk assessment approach be employed in order to address the plethora of security threats to which storage areas for hazardous goods in ports are subject. The increased mobility of people and goods across the globe has been identified as a key factor in the escalation of biosecurity threats, which have the potential to inflict considerable economic, social and environmental damage (Jurdak et al., 2015). The aforementioned threats extend beyond biological hazards to include theft, sabotage, terrorism and unauthorised access to hazardous materials.

In order to ensure the optimum level of physical security in areas designated for the storage of dangerous goods, the implementation of robust access control systems and perimeter protection is imperative. The digitalisation of maritime transport offers opportunities to enhance the security of dangerous goods storage operations (Sanchez-Gonzalez et al., 2019). Technologies such as autonomous vehicles and robotics, artificial intelligence, big data analytics, virtual reality, augmented and mixed reality, and the Internet of Things are being applied to port operations (Sanchez-Gonzalez et al., 2019). The integration of these technologies into comprehensive security management systems is facilitated by cloud computing and other digital infrastructures (Sanchez-Gonzalez et al., 2019). Advancements in sensor technology have facilitated enhanced monitoring of storage conditions and the safety status of hazardous cargo. Bioelectronic noses, which comprise smart chemical sensor arrays combined with bio-receptors, offer the ability to detect volatile organic compounds with precision and specificity (Trung et al., 2018).

The security of areas where dangerous goods are stored in ports is a complex, multi-dimensional challenge requiring comprehensive approaches that integrate physical security, technological solutions, organisational practices and regulatory compliance. The management of these security risks involves a number of factors, including threat assessment and characterisation (Fayet and Rotureau, 2020; Manzoor, 2020), physical security measures (Cozens, 2007; Cowman and Bowers, 2009), technological monitoring systems (Jurdak et al., 2015; Marques et al., 2021; Mrabet et al., 2020), organisational security practices (Bollettino, 2008; Rowley et al., 2013) and emergency preparedness (Cabán-Martinez et al., 2018; Borrero et al., 2015; Bernard and Titov, 2015).

Digitalisation and automation of port operations present a multifaceted landscape, offering the potential to enhance security through advanced monitoring and control capabilities (Sanchez-Gonzalez et al., 2019). However, these advancements also give rise to novel concerns regarding cybersecurity and system reliability (Mrabet et al., 2020). The integration of emerging sensor technologies (Trung et al., 2018; Lobsiger & Stark, 2019; Mochalski et al., 2018) and autonomous surveillance systems (Jurdak et al., 2015) has the potential to significantly enhance the ability to detect and respond to security threats. However, it is imperative to consider the equilibrium between technological advancements and staff training (Manzoor, 2020), organisational coordination (Bollettino, 2008), and regulatory compliance (Allender, 2002).

2.2. Communication in Hazardous Materials Storage Areas

The complexity of dangerous goods in port storage areas requires communication systems capable of rapidly disseminating information regarding specific classes, characteristics and appropriate response protocols. Hazardous cargo incidents each require different response measures and protective actions (Majd et al., 2019). Therefore, communication systems must be able to convey detailed technical information whilst remaining accessible to staff with varying levels of expertise. Biosecurity principles provide additional frameworks for understanding communication requirements in hazardous materials storage areas. Biosecurity is a critical component of the efforts, policies and preparations made to protect human, animal and environmental health against biological threats (Oleas and Robles-Medranda, 2019).

The interconnected nature of port operations requires communication systems capable of interfacing with international standards and protocols (Oleas and Robles-Medranda, 2019). Ports handling dangerous goods must maintain communication capabilities compatible with global biosecurity and biosafety frameworks and ensure that information regarding dangerous goods is effectively shared across organisational and national borders. Communication resilience for port dangerous goods storage areas refers to the ability of information systems to maintain functionality during and after incidents and to enable coordinated response and recovery efforts.

Communication regarding health risks in dangerous goods storage areas must address not only acute chemical exposures but also potential biological hazards and long-term health effects (Lapid et al., 2021). Effective communication systems should include mechanisms for reporting exposures, monitoring health outcomes, and disseminating information on protective measures. The financial and human costs associated with inadequate hazard communication underscore the importance of investing in a robust communication infrastructure. Personal protective equipment (PPE) is defined as equipment that protects the user's body against health and safety risks in the workplace (Chakraborti et al., 2018). The relationship between PPE and communication in hazardous substance storage areas is two-way: effective communication is necessary for the correct selection and use of PPE, but PPE requirements may affect communication capabilities (for example, respiratory protection may hinder verbal communication).

Skin conditions resulting from PPE use have been documented, highlighting the need for communication regarding the protective benefits and potential side effects of safety equipment (Chakraborti et al., 2018). In port hazardous cargo storage areas, workers must receive clear communication regarding appropriate PPE for specific hazards, correct donning and doffing procedures, and signs of equipment failure or inadequate protection. As hazardous conditions can change rapidly during operations, this communication must be continuous. In port hazardous cargo storage areas, this includes communication between supervisors and workers, among work teams, and with external emergency response teams. The emphasis on empathetic communication acknowledges that workers in hazardous environments may experience stress and anxiety, which can affect their ability to process safety information and act accordingly.

For hazardous cargo storage areas in ports, remote communication technologies can facilitate real-time consultation with hazardous materials experts, remote monitoring of storage conditions, and coordination with emergency response resources outside the facility. In port hazardous cargo communication, this involves ensuring that remote communication systems meet regulatory requirements, that information transmitted remotely is secure and accurate, and that liability issues are addressed through appropriate policies and procedures. The ethical dimensions of hazard communication include informed consent (ensuring that workers understand the risks before accepting hazardous tasks), transparency (providing complete and accurate information about hazards) and equity (ensuring that all workers have access to safety information regardless of language or literacy status) (Lukaszyk et al., 2018).

2.3. Authorised Personnel Access to Hazardous Materials Storage Areas in Ports

The management and control of access to hazardous materials storage facilities represent a critical intersection in terms of occupational health, environmental safety and regulatory compliance. By their very nature, hazardous materials pose significant risks to human health and the environment, and strict protocols are required for access control, personnel protection and emergency preparedness. The disposal and management of hazardous waste is a global issue that requires systematic approaches to minimise exposure risks (Kim et al., 2015). It is imperative to comprehend the health implications of exposure to hazardous waste when formulating efficacious access control systems. A systematic review was conducted to evaluate the evidence on the health effects of exposure to hazardous waste (Kim et al., 2015). The review employed transparent and predefined methods to assess the relationship between exposure and adverse health outcomes.

The assessment of potential exposure scenarios necessitates a comprehensive consideration of the myriad ways in which hazardous substances can affect workers. This comprehensive approach to exposure assessment can be directly applied to hazardous substance storage environments where workers may be exposed via multiple routes, including inhalation, skin contact and ingestion. The identification of core competencies for personnel handling hazardous substances is of crucial importance for the effective implementation of entry control measures. Research on hazardous goods transport drivers has identified the core competencies required to manage emergencies and accidents (Woskie, 2010). Those engaged in the transportation of hazardous materials are entrusted with the responsibility of ensuring the secure delivery of such consignments. They are confronted with a multitude of challenges during the execution of their duties. In addition to their primary role, these individuals function as first responders in situations of emergency and accidents (Woskie, 2010). It is imperative to note that these competency requirements are equally applicable to warehouse personnel, who are expected to demonstrate preparedness to respond to incidents occurring within storage facilities.

The assurance of a secure environment within facilities engaged in the management of hazardous materials is contingent not solely on infrastructural provisions, but also on the equipment and materials employed within these facilities (Wang et al., 2019). The management and maintenance of safe environments require consideration of numerous factors, including cleanliness, appropriate storage conditions and suitable facility design (Wang et al., 2019). In order to ensure comprehensive safety, it is essential that access control systems are integrated with broader facility management approaches. The advent of increasingly sophisticated wearable and implantable devices, integrated with wireless sensors, has led to a proliferation of monitoring applications for hazardous material storage environments (Riess and Hoelzer, 2020). These technologies have the capacity to enhance access control by monitoring workers' risks and locations in real time. The advent of sophisticated detection technologies has profound implications for the realm of access control in hazardous cargo storage facilities. The evolution of process safety has highlighted the importance of continuous improvement in safety management systems (Hao and Foster, 2008). Contemporary approaches to the management of hazardous materials recognise the necessity for safety systems to evolve in order to address emerging hazards and to incorporate lessons learned from incidents. It is imperative that access control systems undergo periodic review and update in accordance with operational experience and advancements in safety science.

2.4. Storage Areas for Special Hazardous Cargoes in Ports

The global impact of the novel Coronavirus (SARS-CoV-2) pandemic has had a considerable effect on the management of port operations worldwide, including the handling of dangerous goods. The imposition of full or partial lockdowns by countries worldwide resulted in the suspension of most economic activities until the outbreak was contained, and the decisions taken by governments had a significant impact on maritime operations (Naghii, 2005). The repercussions of these disruptions have encompassed the domains of supply chains for hazardous materials, alterations in storage requirements, and the introduction of novel protocols for worker safety. The pandemic also exposed weaknesses in port infrastructure and operations that affect the management of dangerous cargo. A confluence of factors, including diminished staffing levels, disruptions to the supply chain for safety equipment, and fluctuations in cargo volumes, has adversely impacted the capacity of ports to uphold optimal safety standards.

Those engaged in the storage and transportation of hazardous materials are exposed to considerable occupational health hazards. Observations of hepatotoxicity in workers due to elevated chloroform concentrations underscore the capacity for chemical exposure in industrial contexts to engender deleterious health consequences (Menhat et al., 2021). Those engaged in the handling of hazardous cargo may also be exposed to similar risks, necessitating comprehensive exposure monitoring and control measures. The characterisation of occupational exposures in port environments necessitates a systematic assessment of potential hazards, exposure routes and the at-risk workforce. This includes consideration of both acute exposure scenarios, such as spills or container breaches, and chronic exposures arising from routine handling operations. It is imperative that storage facility design incorporates engineering controls with the objective of minimising worker exposure. These designs must be supported by administrative controls and personal protective equipment.

The storage of biological hazardous substances necessitates specialised infrastructure that prevents release whilst maintaining appropriate environmental conditions. The principles of compartmentalisation, a fundamental characteristic of living cells that ensures the regulation of biological processes without interference from external influences, can be applied to the design of storage facilities (Modica et al., 2018). The concept of compartmentalisation entails the physical separation of incompatible substances, the use of secondary containment systems, and the implementation of environmental controls. Storage facilities for biohazardous cargo must address temperature control, humidity management and air handling to protect material integrity whilst safeguarding staff and the environment. The design of such facilities must account for both routine operations and emergency scenarios, including power failures, natural disasters and security breaches.

The storage of specific hazardous cargo classes in ports poses a multifaceted challenge, necessitating the integration of technical, regulatory and operational considerations. The characterisation of physical hazards, the implementation of appropriate containment and monitoring systems, and the development of effective emergency response capabilities are fundamental elements of safe hazardous cargo storage. The experience of the pandemic has demonstrated the paramount importance of resilience and adaptability in port operations, including the management of hazardous cargo. It is reasonable to hypothesise that future developments in this field are likely to be shaped by advancements in detection and containment technologies, evolving regulatory frameworks, and the impacts of climate change on port infrastructure. It is incumbent upon port authorities to be cognisant of these trends and to perpetually enhance their safe storage capabilities for dangerous goods. The primary concern remains the protection of personnel, communities and the environment from the risks associated with the transportation of dangerous goods. This issue necessitates constant attention and investment.

2.5. Special Operations in Hazardous Cargo Storage Areas at Ports

The evaluation of hazardous materials constitutes a pivotal element of risk management in port storage operations. It is important to note that this highlights the complexity of assessing dangerous goods and their potential impacts (Aschberger et al., 2017). This framework for chemical assessment can be directly applied to the requirements for the classification and segregation of dangerous cargoes in port storage areas. The examination of initiatives and methodologies aimed at reducing CO_2 emissions and the impacts of climate change in ports underscores the importance of integrating environmental considerations into all aspects of port operations, including the storage of dangerous cargo (Azarkamand et al., 2020). The environmental dimension of hazardous cargo storage extends beyond direct emissions to include pollution incidents, leaks and releases that can affect air, water and soil quality. The concept of holistic environmental policies, which emerged approximately 40 years ago from a simple combination of technical activities in waste management, represent the most advanced level of environmental policy (Wiesmeth and Häckl, 2016). These approaches to environmental policy seek to influence economic actors to adopt environmentally friendly behaviours. In the context of ports, this involves the design and operation of hazardous cargo storage areas that minimise environmental risk (Wiesmeth and Häckl, 2016).

The establishment of a robust safety culture is of paramount importance for the secure operation of hazardous cargo storage areas. Safety culture is defined as a function of interrelated processes that facilitate organisational learning, leadership commitment and employee participation (Singer & Vogus, 2013). The findings of this research demonstrate that technical controls and procedural measures alone are insufficient for port operations involving dangerous goods, and that an appropriate organisational culture that prioritises safety is also necessary. In order to maintain the integrity of dangerous goods storage systems, it is essential to integrate safety considerations into all levels of decision-making, from strategic planning to day-to-day operations. The implementation of effective warning systems and communication protocols is of paramount importance in the context of hazardous cargo storage area operations. A seminal study on warning systems (Rogers et al., 2000) defined the warning process in terms of four components: notification, coding, comprehension and compliance. The relevant variables are classified as person variables, which refer to individual characteristics, and system variables, which refer to the characteristics of the warning system itself (Rogers et al., 2000). This framework can be directly applied to the design of warning systems for hazardous cargo areas, where workers must be able to quickly recognise, understand and respond appropriately to hazard warnings.

The segregation of incompatible hazardous materials constitutes a fundamental principle in the domain of hazardous cargo storage. Research on the subject of overlapping risks and failure modes has provided relevant analytical frameworks for understanding how different hazards can interact (Hardwick et al., 2003). It is imperative that hazardous cargo storage areas are designed with a comprehensive consideration of potential failure modes, encompassing the risks of fire, explosion, toxic release, and environmental contamination. The storage arrangements must be meticulously engineered to avert cascading failures, ensuring the safety of the storage environment. The reverse logistics of hazardous materials, including the return and disposal of hazardous cargo, is a significant consideration for port operations. It is imperative that port hazardous cargo storage areas are designed to accommodate not only the forward flow of hazardous materials, but also the reverse flow of damaged, expired or rejected hazardous cargo. The establishment of adequate facilities is imperative for the purpose of inspecting, repackaging and temporarily storing materials designated for disposal or return transport.

2.6. The Need for an Emergency Response Unit

The effective management of emergency responses is of paramount importance in the context of incidents involving dangerous goods at port facilities. It is imperative that response protocols address a range of scenarios, from minor to major spills, and that these protocols be coordinated with local emergency services, regulatory bodies and other relevant stakeholders. Preparedness is vital for ensuring an adequate response to the accidental or deliberate release of hazardous materials (Baptista et al., 2015). The development of disaster response capacity is contingent upon the implementation of structured training programmes and assessment methodologies. Exercises grounded in the paradigm of simulated incident scenarios have been demonstrated to be efficacious training methodologies for personnel and hazard response teams. Structured assessments have been identified as significant mechanisms for evaluating preparedness (Baptista et al., 2015). The release of biological hazardous materials has the potential to impact a significant number of individuals; consequently, preparedness for hazardous material storage operations is of the utmost importance (Baptista et al., 2015). The storage of certain hazardous materials poses explosion risks that must be addressed through access control systems. A case in point is the ammonium nitrate explosion in Beirut, which serves to illustrate the destructive potential of hazardous materials that are not stored appropriately. The generation of supersonic pressure and heat in such incidents has the potential to cause catastrophic damage, thereby emphasising the significance of adequate storage and the implementation of effective access control measures.

The effective management of hazardous materials in ports is contingent upon the precise characterisation of these materials' physical and chemical properties. Specialist organisations with decades of experience in this field have developed and implemented state-of-the-art experimental facilities that enable characterisation at different scales and under various conditions to examine all potential accident scenarios (Vero et al., 2019). This comprehensive approach to hazard characterisation is essential for establishing appropriate storage protocols and emergency response procedures within port facilities. In light of the fact that chemical incidents in ports have the potential to escalate rapidly and have a significant impact on surrounding communities, the correlation between hospital preparedness and port emergency response is of particular importance. The preparedness framework must account for the potential number of casualties and specific types of chemical exposure that may result from incidents involving hazardous cargo (Majd et al., 2019). This necessitates the establishment of collaborative frameworks between port authorities, emergency services and healthcare facilities, with the objective of ensuring the efficacy of response capabilities (Majd et al., 2019).

The development of incident response protocols necessitates a systematic analysis of potential scenarios and their consequences. This process entails a comprehensive evaluation of the specific hazards posed by stored materials, the vulnerability of the surrounding population and environment, and the resources available for response. It is imperative to recognise the significance of consistent training and drills in ensuring the preservation of response capabilities.

It is evident that a comprehensive risk assessment should be the foundation upon which emergency response planning for hazardous cargo storage areas in ports is constructed. This assertion is supported by an analysis of the available evidence. Emergency response plans should be formulated in such a manner as to incorporate all relevant stakeholders, including but not limited to port authorities, emergency services, hospitals and public health agencies (Majd et al., 2019). It is imperative that these plans delineate explicit roles and responsibilities, establish communication protocols, and devise coordination mechanisms. It is imperative that this assessment identifies all hazardous substances that are currently in existence. Furthermore, it is essential that the storage conditions of these substances are evaluated, and that the potential consequences of various incident scenarios are assessed. In order to ensure that emergency response preparedness is maintained and any existing gaps in preparedness are identified, it is essential that regular exercises are carried out. It is imperative that exercise programmes encompass a diverse array of exercises, including tabletop exercises, functional exercises, and full-scale exercises that evaluate all dimensions of the emergency response framework. It is imperative that hospital preparedness plans for chemical incidents are also subjected to regular exercises of a similar nature (Majd et al., 2019). In the context of port operations, this research underscores the significance of formulating comprehensive emergency response strategies that encompass the allocation of resources during incidents involving hazardous cargo. The probability of mass casualties resulting from hazardous cargo incidents necessitates the development of emergency response capacity for coordination with local emergency services and medical intervention.

3. LITERATURE

A comprehensive literature review has been conducted on the storage operations of dangerous goods in ports, and a concise discussion of previous studies is provided below.

In their study, entitled 'Integrated Risk Assessment of a Dangerous Goods Container Terminal', Taubert et al. (2023) combined cause-and-effect analysis, the Analytic Hierarchy Process (AHP) and the Delphi method to develop and propose four causal criteria with 14 indicators and two outcome criteria with five indicators for the transport and storage of HNS in ports. The aforementioned criteria were applied to 30 ports in northern Vietnam. Moreover, it was established that the primary concern pertaining to environmental hazards in HNS handling and storage operations is attributable to the environmental management practices employed within port settings.

In their study, Rekik et al. (2015) present a model of a multi-agent-based container stacking system for storing different types of containers, including those containing dangerous goods. This study is titled 'Real-Time Stacking System for dangerous containers in seaport terminals'.

In their 2014 study, Hamidou and colleagues (2014) proposed a hybrid model that utilises Cellular Automata and a Multi-Agent System (MAS) to address the issue of hazardous container storage. This study, titled 'Management of dangerous goods in container terminals using the MAS model', is a seminal piece of research in the field. The objective of this initiative is to enhance safety by refining the method of handling hazardous containers within the terminal. In the model, container criteria were considered with the aim of using a Multi-Agent System for decision support software and a Cellular Automata to model the terminal.

In their study, entitled 'An analysis of risks and preventive measures related to dangerous cargo operations in ports using a fuzzy multi-criteria integrated model', Yeğin and Yorulmaz (2023) employed the Fuzzy DEMATEL and ANP methods. The research findings indicate that the measure which is considered to be of the utmost importance is the classification, labelling, control and storage of dangerous goods by port personnel in accordance with the IMDG Code and current legislation.

In their study, Unal and Alkan (2023) sought to determine the key determining factors in dangerous goods storage operations at container terminals. Their study, titled 'An Analysis of Container Terminals' Approaches to Dangerous Goods Operations and Cargo Structures in the Marmara Region', was published in the academic journal. The researchers found that compliance with the IMDG Code and risk-based layout planning were the key determining factors in dangerous goods storage operations at container terminals. In the majority of terminals, block planning is conducted in accordance with segregation rules, thereby minimising the storage duration of high-risk cargoes.

In his study, Zorba (2009) emphasises that the storage of hazardous cargoes within port areas must be conducted within the framework of classification and segregation rules based on the IMDG Code. The allocation of storage areas, ensuring access for fire and emergency services, and minimising waiting times, are key safety elements.

Despite the fact that prior studies have investigated hazardous cargo operations and risk management in ports, there has been limited research specifically focusing on operational prioritisation in the context of dangerous goods container storage. The present study aims to address this lacuna by evaluating the relative importance of storage operation criteria using the AHP method.

4. METHOD

In this study, international legal regulations were examined in detail; the six storage operation priorities identified within the framework of these regulations were communicated via a questionnaire to 20 container ports operating in Türkiye that participated in the research. The participating ports were tasked with the evaluation of the pertinent criteria and their subsequent ranking according to priority. The data obtained were analysed using the Analytic Hierarchy Process (AHP), a Multi-Criteria Decision Making (MCDM) method.

As posited by Ho and Ma (2018), the structural underpinnings of any decision problem are characterised by a multifaceted framework comprising multiple criteria and sub-criteria, which can be systematically evaluated through pairwise comparisons. This approach involves the transformation of complex decision problems into a hierarchical structure, thereby facilitating the division of these problems into more manageable sub-components. This, in turn, results in a reduction in the cognitive load on decision-makers and a rationalisation of the analytical evaluation process.

A distinctive feature of the AHP methodology is its capacity to measure and control inconsistencies that may arise in human judgement. The method has been demonstrated to facilitate the quantification of preferences, whilst also enabling the assessment of consistency between these preferences via the consistency ratio. In this respect, AHP has been demonstrated to contribute to the reduction of biases that may arise from subjective judgements in the decision-making process (Dey and Ramcharan, 2008). Moreover, the method's reliance on mathematical foundations enables it to be used as a reliable and systematic tool in fields involving multi-dimensional and multi-criteria evaluations, such as financial analysis and project assessments (Daoutis et al., 2023).

Recent advancements in the relevant literature suggest that AHP has undergone an evolutionary process, adapting to address increasingly intricate decision-making challenges. In this context, the Analytic Network Process (ANP), developed to expand the scope of the method, incorporates the interdependencies and feedback relationships between criteria and sub-criteria into the model (Liu et al., 2014). This underscores the methodological flexibility of AHP-based approaches and their applicability in dynamic decision-making environments.

The application process for the AHP is typically comprised of the following stages:

The initial step in this process is to define the decision problem and the fundamental objective of the research in clear and precise terms.

The Analytic Hierarchy Process (AHP), first developed by Thomas L. Saaty in 1980, is one of the most widely used techniques among Multi-Criteria Decision Making methods in the present day. The method facilitates the modelling of complex decision-making problems within a hierarchical structure. It offers a systematic analysis process by breaking down the problem into levels of objective, criteria, sub-criteria and alternatives.

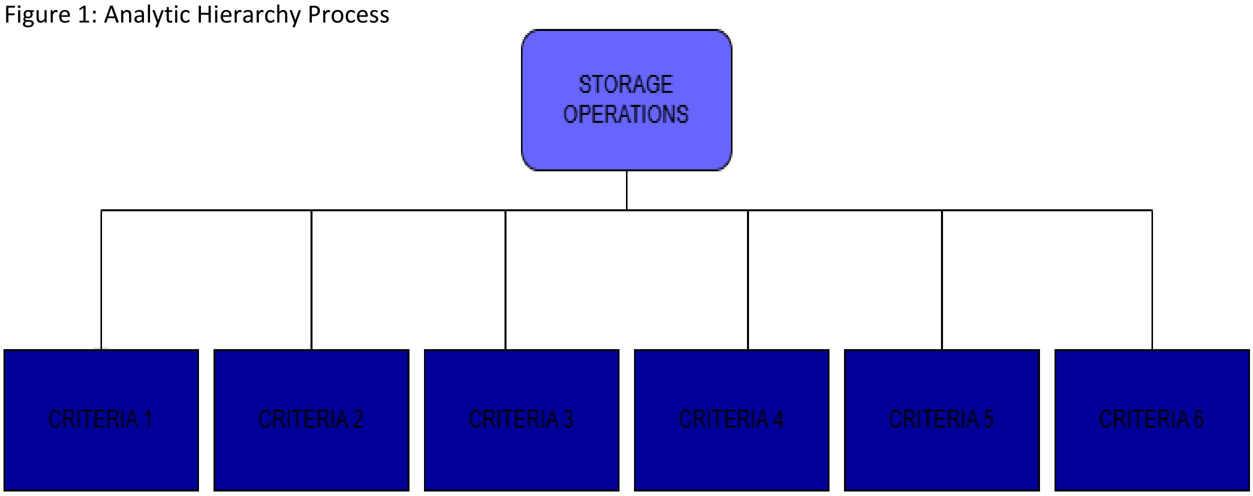
The second step in the process is to define the criteria, and where applicable, the sub-criteria, that serve to achieve the objective that has been defined.

The third step in the process is to identify the decision alternatives to be evaluated under each criterion.

The fourth step in the process is the creation of a hierarchical model comprising the objective, criterion, sub-criterion, alternative structure, and preparation of pairwise comparison matrices.

It is evident that the configuration under consideration facilitates the systematic and consistent analysis of the decision problem. The relative priority ranking of alternatives can be determined based on the weights obtained.

Figure 1: Analytic Hierarchy Process



The first stage in AHP is the establishment of the hierarchical structure of the decision problem. Following this stage, the methodological process consists of the following basic steps: (i) the creation of a Comparison Matrix to facilitate the execution of AHP operations, (ii) the conversion of this matrix into a Priority Vector, and (iii) the calculation of the Consistency Ratio.

In AHP, relative or absolute measures must be used to carry out pairwise comparisons. The judgements obtained in this way are converted into a comparison matrix (Timor, 2011).

Basic Characteristics of the Pairwise Comparison Matrix:

1. The pairwise comparison matrix is a square matrix consisting of positive values.

2. If the matrix is fully consistent:

$$a_{ij} \times a_{jk} = a_{ik} (i, j, k = 1, \dots n)$$

3. The principle of reciprocity:

$$a_{ji} = \frac{1}{a_i j}$$

4. Total number of comparisons for criterion n

$$\frac{n(n-1)}{2}$$

5. The greatest intrinsic value ($\lambda_{\max}$) The corresponding eigenvector is the weight (priority) vector.

6. The diagonal elements of the matrix are equal to 1. (Saaty, 2000).

The priority vector is represented as W = (w1, w2, …, wn) from the pairwise comparison matrix, and each w_i represents the relative weight of the corresponding criterion.

The AHP Solution Process:

Step 1: Creation of the comparison matrix.

Step 2: Normalisation of the matrix to convert it into a priority vector.

Step 3: Calculation of the Consistency Ratio (CR).

The consistency ratio measures the consistency between comparisons. A CR value below 0.10 indicates an acceptable level of consistency. If CR > 0.10, the comparisons must be reviewed.

1. The sum of each column in the comparison matrix is calculated.

2. Each element in a column is divided by the total of that column to obtain the normalised matrix.

3. The arithmetic mean of each row in the normalised matrix is taken to calculate the priority vector.

4. The resulting priority vector is multiplied by the initial comparison matrix to form the "Overall Priority Matrix".

5. The consistency index (CI) is calculated using the following formula:

$$c_I = \frac{\lambda_{max} - n}{n-1}$$

This λ_{max}, It represents the largest eigenvalue of the square matrix. To calculate this value, each element in the matrix of priorities is divided by the corresponding element in the priority vector, and the average of the resulting values is taken.

The Consistency Ratio (CR) is:

$$CR = \frac{CI}{RI}$$

Here, RI denotes the Random Index value, which is selected from a standard table generated based on the number of criteria (Timor, 2011).

A CR value of less than 0.10 indicates acceptable consistency. If CR > 0.10, the comparisons must be reviewed.

The Analytic Hierarchy Process (AHP) is recognised as a critical methodology within decision-making frameworks, enabling the structured, consistent and comprehensive analysis of complex problems, particularly in the context of evaluating ports within a logistics framework. It has been demonstrated in the literature that AHP enhances applications across a wide range of fields, particularly in project management and environmental planning, and makes significant contributions to decision-support processes.

In the field of Multi-Criteria Decision Making, AHP continues to be significant in that it offers a systematic and hierarchical approach to complex problems. The method's ability to integrate subjective judgements within a mathematical and analytical framework provides a significant advantage for decision-makers, particularly in multi-dimensional and uncertain decision-making environments.

In this study, feedback obtained from ports was analysed using the Super Decisions software package. The results of the analysis are presented in detail in tabular form in the findings section. Furthermore, the average weights of the priorities identified by the ports regarding their handling operations have been presented both numerically and visually to provide a practical perspective.

5. EVALUATION

Hazardous cargo storage operations are considered to be one of the most sensitive and high-risk stages of the logistics activities carried out at container terminals. These operations encompass the entire process, from the moment containers containing hazardous materials enter the terminal site, through to the loading of the relevant cargo onto a vessel, its transfer to another mode of transport, or its departure from the terminal site. In light of the physical, chemical and environmental characteristics of dangerous goods, it is imperative that strict compliance with national and international regulations is observed during their temporary storage within the terminal area. In this context, storage activities are of critical importance in relation to operational efficiency, occupational health and safety, environmental protection and port security.

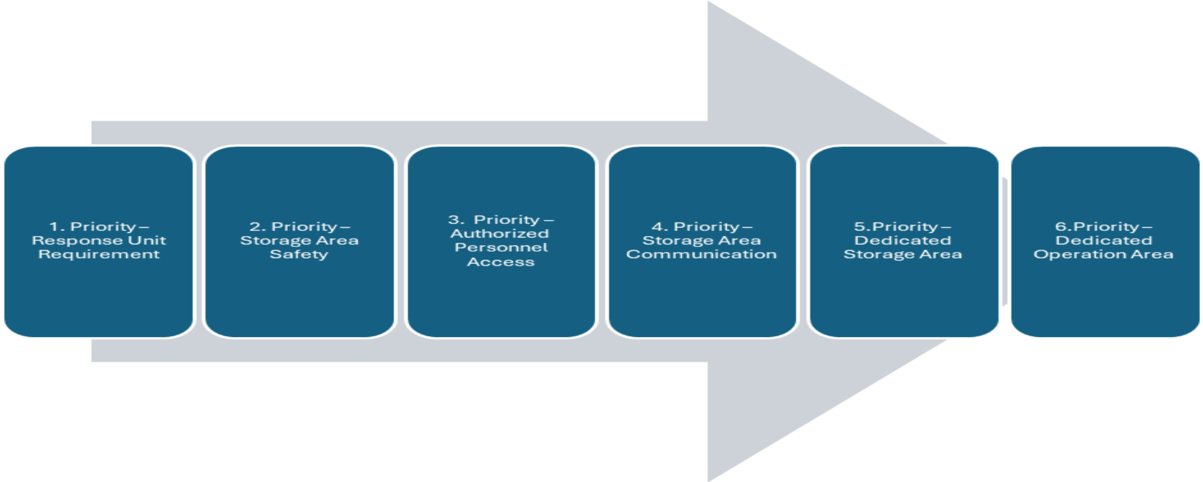
Containers holding dangerous goods are subject to constant supervision and control whilst on the terminal site. The storage areas where containers are to be placed are determined by taking into account the hazard classes of the cargo, their compatibility status and potential reaction risks. Hazardous cargoes are classified in accordance with the provisions of the International Maritime Dangerous Goods Code (IMDG Code), which is published by the International Maritime Organisation. Segregation rules appropriate to these classes are applied. In this context, specific safety distances are maintained between cargoes that could react with one another or pose a safety risk if stored together; the stacking and positioning of containers is planned in accordance with these technical requirements. Furthermore, specialised dangerous goods storage areas established within the terminal site are supported by fire-extinguishing systems, spill control equipment, emergency response equipment and environmental protection infrastructure, with the aim of ensuring the highest level of operational safety.

It is imperative to note that, throughout the storage process, the physical condition of the containers is meticulously examined at regular intervals. In addition, potential risk indicators such as temperature rise, gas emission, leakage or packaging deformation are methodically monitored, depending on the nature of the cargo. In accordance with operational requirements, technical and administrative interventions—such as the repositioning of containers, their transfer to isolation areas, or the implementation of special safety measures—may be carried out. These interventions are of great importance in ensuring the continuity of terminal operations and in bringing potential risks under control before they escalate.

In order to ensure that the storage of hazardous cargo is conducted safely and effectively, it is essential that personnel at the terminal possess the relevant technical knowledge and operational experience. It is imperative to be prepared for the possibility of extraordinary situations arising during storage processes. Such situations may include accidents, fires, explosions, chemical reactions, leaks or environmental contamination. This preparation is considered a fundamental element of the risk management approaches implemented in ports. In this context, port operators prepare emergency response plans, staff undergo regular training and drills, and coordination mechanisms are established with the relevant authorities. This approach has been demonstrated to enhance operational safety and ensure the ability to respond swiftly and effectively in the event of an emergency.

As indicated by the extant literature, there exists a variety of criteria that are prioritised for the safe and effective management of dangerous goods storage operations. Consequently, a comprehensive literature review has identified six fundamental criteria for the evaluation of dangerous goods storage operations. The present study employs these criteria as its analytical framework, thereby enabling the analysis of ports' practices regarding dangerous goods management and their operational safety approaches. The prioritisation of these criteria based on their importance levels was assessed using the Analytic Hierarchy Process, a multi-criteria decision-making method, and the resulting order of importance is presented in Figure 2.

Figure 2: Priority Ranking in Dangerous Goods Container Storage Operations



The primacy of the 'Need for an Emergency Response Unit' criterion in the Figure 2 priority list is attributable to the inherent risks associated with hazardous materials storage operations, characterised by high-impact and low-tolerance risks. Hazardous goods storage areas are susceptible to a range of potential hazards, including fire, explosion, chemical leakage and the release of toxic gases. These incidents can lead to extensive physical damage, environmental degradation and significant economic losses, if they occur. It is acknowledged that the complete prevention of such incidents is not always feasible. Consequently, the capacity to minimise the consequences of an incident is identified as a pivotal component in risk management literature. Indeed, the capacity of personnel working with hazardous materials to respond swiftly and effectively to emergencies is one of the fundamental determinants of system safety. In this context, the emergency response unit represents the system's final line of defence against potential accidents and, due to its capacity to directly mitigate the severity of risk, holds a higher priority than other criteria.

The Storage Area Safety criterion, which ranks second, refers to the structural and technical safety requirements aimed at preventing risks from arising. The assurance of a secure environment within facilities encompassing hazardous materials is contingent not solely on the existence of physical infrastructure, but also on the adequacy of the equipment employed, the congruence of facility design with safety standards, and the probity of operational procedures. It is imperative to consider fundamental preventive safety components that reduce the likelihood of potential risks materialising. Such components include, but are not limited to, the following: fire detection and suppression systems, effective ventilation mechanisms, impermeable floor structures, appropriate segregation practices and physical barriers. This criterion constitutes a preventive control mechanism, with the objective of averting the emergence of risk, as opposed to the direct intervention during a crisis. In evaluating the hierarchical arrangement of preventive and corrective control mechanisms in safety management, the placement of warehouse area safety in second position is determined to be consistent with a systematic risk management approach.

The 'Authorised Personnel Access' criterion, which was ranked third, reflects the decisive role of the human factor in hazardous materials operations. The study emphasises that access control systems must be addressed not merely as a physical security element, but within an integrated framework with facility management systems. The sustainability of security can be ensured not only through technical measures, but also through the establishment of a robust safety culture and the training of a well-qualified workforce. Permission for access to storage areas must be granted only to authorised personnel who have undergone the necessary training. Failing to do so can result in a number of potential risks, including procedural breaches, incorrect handling practices, equipment usage errors, and even sabotage. However, this criterion is not evaluated as a direct source of physical danger; rather, it is considered a factor that establishes the conditions for potential risks to emerge. Therefore, whilst it has a lower priority value compared to emergency response capacity and structural safety elements, its placement in third position is a methodologically consistent result due to the critical impact of the human factor on operational safety.

The 'Storage Area Communication' criterion, which was ranked fourth, highlights the importance of coordination and information flow in risk management processes. The importance of effective communication infrastructure and early warning systems in ensuring the safe execution of hazardous cargo operations cannot be overstated. As indicated by the extant literature, warning processes consist of the following stages: the transmission of information, encoding, correct perception by the user, and the provision of an appropriate response. The effectiveness of these processes is influenced by both individual and systemic factors. While the communication infrastructure does not function as a direct eliminator of risk, it does serve as a supportive mechanism that prevents incidents from escalating and optimises response times. Consequently, its placement in accordance with criteria representing preventive safety measures and response capacity indicates a rational sequence in terms of systematic safety prioritisation.

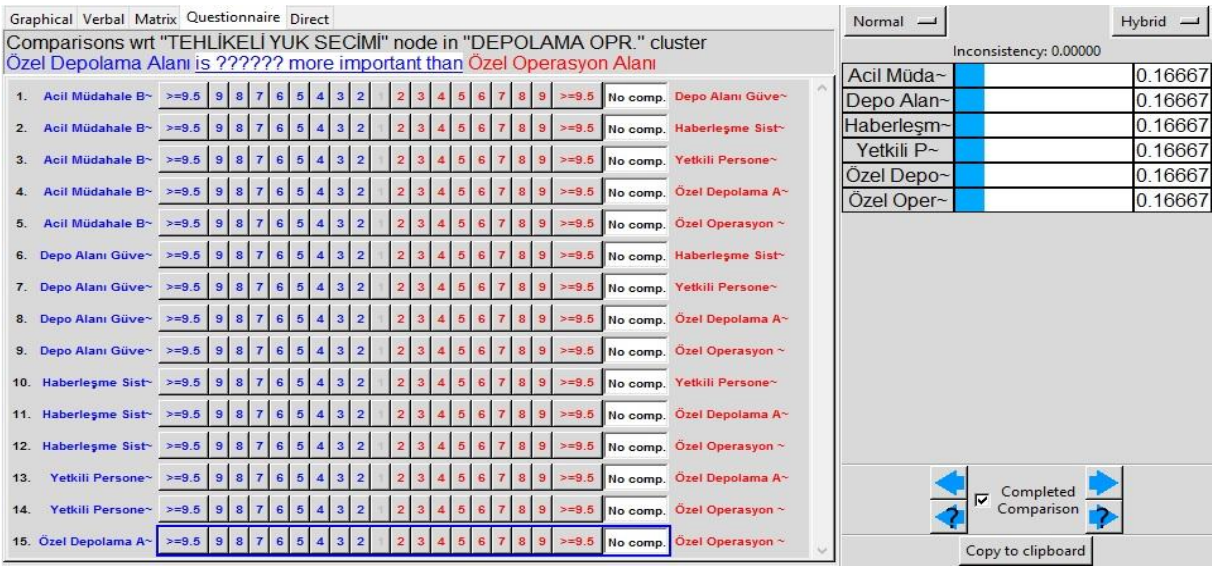
The 'Dedicated Storage Area' criterion, which was ranked fifth, refers to practices aimed at segregating specific hazardous cargo classes and storing them under controlled conditions. It is particularly during periods of global crises and supply chain disruptions that the importance of storage capacity management, operational resilience and dedicated area planning has become more pronounced. However, specialised storage areas are generally designed for specific risk categories and do not form part of the fundamental safety elements encompassing all operational processes. While these measures do engender a risk-mitigating effect throughout the system, they do not assume the same significance as structural safety infrastructure or emergency response capacity. Consequently, the criterion's placement in fifth position is regarded as a methodologically consistent outcome, considering its scope and area of impact.

The 'Special Operations Area' criterion, which is assigned the lowest rank, primarily represents the dimension of operational organisation and process management. The overarching objective of these areas is to ensure that specific handling activities or control processes are carried out under safer conditions. However, it should be noted that these measures do not constitute a fundamental security barrier with a direct risk-reducing function. In the Analytic Hierarchy Process (AHP) method, decision-makers evaluate criteria according to their relative impact levels and assign higher weight values to elements possessing the highest risk-reduction capacity on system security. In this context, special operational areas are assessed as one of the supporting components of safety; however, they do not play as decisive a role as fundamental safety mechanisms such as emergency response capacity, structural safety measures or access control. Consequently, the fact that this criterion is ranked sixth is an expected and methodologically justifiable result.

When assessed in total, the resulting ranking corresponds to the risk prioritisation approach that is accepted in the field of security management literature. The priority ranking reveals a hierarchical security architecture that progresses from direct intervention capacity during a crisis to structural security measures, human factor control, communication infrastructure and operational organisation elements. This situation demonstrates that safety management in hazardous materials storage activities must be addressed within a multi-layered structure, and that risk reduction strategies must be built upon complementary preventive, control and intervention mechanisms.

Questionnaires were prepared to evaluate previously established criteria regarding hazardous cargo storage operations. These were administered verbally through face-to-face and remote interviews with terminals. In the context of this study, responses obtained from a total of 20 terminals were analysed using Super Decisions software.

Figure 3: Screenshot of the Computer Programme for the Evaluation of Storage Operation Criteria.



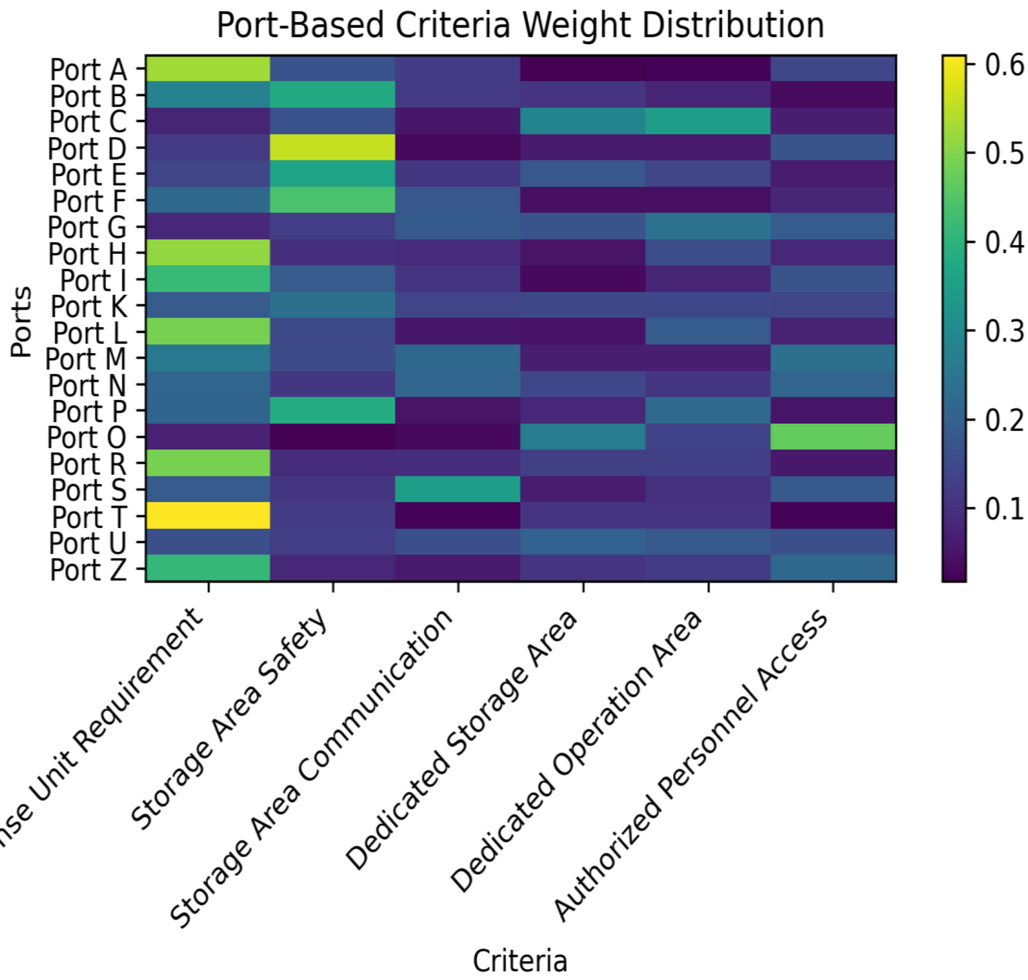
The data obtained from the analysis of the responses provided by the terminals in the Super Decisions programme is presented in Table 1 below. The following table illustrates the ranking of the importance levels assigned by each terminal to the criteria identified for container storage operations. In order to protect the confidentiality of the terminals' identifying information included in the study, the names of the terminals have been coded and their actual names have not been disclosed.

Table 1: Container Terminal Storage Operation Criteria Distributions

Ports	Response Unit Requirement	Storage Area Safety	Storage Area Communication	Dedicated Storage Area	Dedicated Operation Area	Authorized Personnel Access
Port A	0,52770	0,16625	0,12011	0,01792	0,02362	0,14440
Port B	0,28030	0,37762	0,11945	0,10886	0,07821	0,03556
Port C	0,07950	0,16584	0,05370	0,28411	0,34851	0,06834
Port D	0,11835	0,55782	0,03202	0,05991	0,05991	0,17199
Port E	0,14107	0,36135	0,11303	0,17937	0,14107	0,06411
Port F	0,21544	0,44056	0,17803	0,04307	0,04236	0,08054
Port G	0,08636	0,12514	0,18576	0,17139	0,24136	0,18999
Port H	0,51453	0,09990	0,09202	0,04808	0,15966	0,08581
Port I	0,41993	0,18838	0,10922	0,03400	0,07888	0,16959
Port K	0,18858	0,23668	0,14175	0,14562	0,14562	0,14175
Port L	0,48838	0,14811	0,05345	0,04575	0,19051	0,07380
Port M	0,25791	0,15453	0,21655	0,06689	0,06689	0,23723
Port N	0,21050	0,11287	0,21050	0,14354	0,11209	0,21050
Port P	0,20798	0,38306	0,04929	0,08582	0,22307	0,05078
Port O	0,07321	0,01926	0,03347	0,26835	0,13578	0,46993
Port R	0,49150	0,09470	0,09470	0,13071	0,13071	0,05768
Port S	0,18721	0,11252	0,35041	0,06493	0,10159	0,18334
Port T	0,60953	0,12371	0,02367	0,10971	0,10971	0,02367
Port U	0,16260	0,12567	0,16261	0,20347	0,18304	0,16261
Port Z	0,41085	0,08451	0,05987	0,10839	0,11962	0,21676

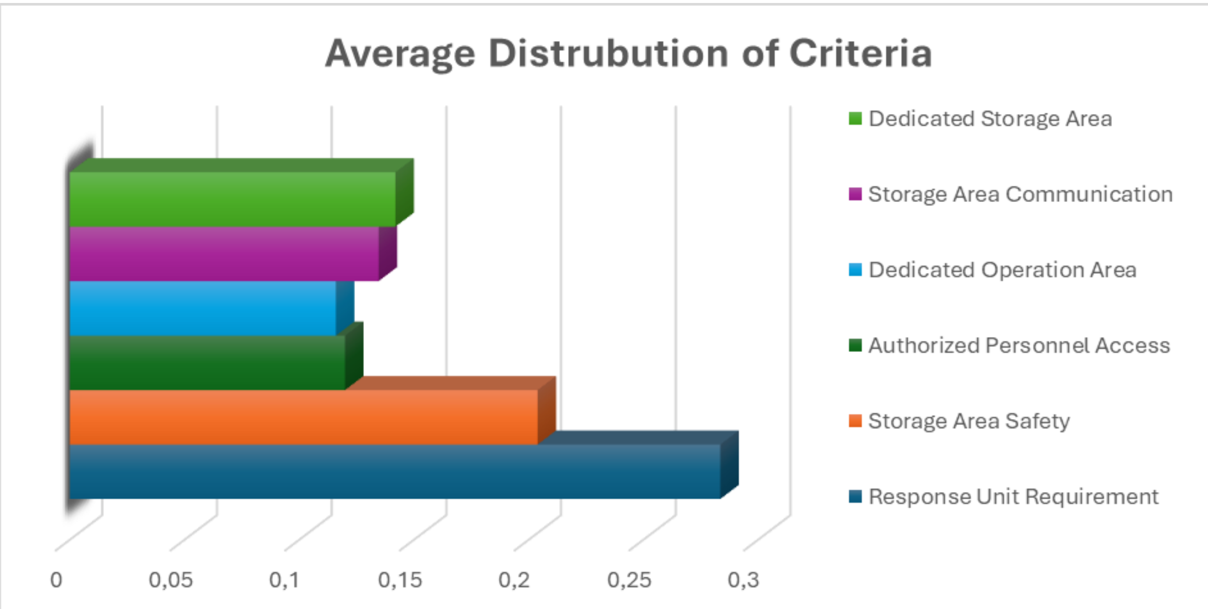
As demonstrated in the above table, terminals allocate varying degrees of priority to different criteria. The findings indicate that the operational planning criterion is accorded the highest priority by the terminals. This finding underscores the pivotal function of planning in operational processes. The priorities assigned by ports to hazardous cargo storage operations are presented in the Port–Criteria Heatmap shown in Figure 4 below.

Figure 4: Port–Criteria Heatmap



The average values for the priority criteria, calculated based on data from 20 terminals operating across Türkiye, are presented in Figure 5 below.

Figure 5: Distributions of Storage Operation Criteria in Ports Preferences.



The results of the Analytic Hierarchy Process (AHP) analysis presented in Table 1 and Figure 5 reveal the relative importance levels of the criteria relating to hazardous cargo container storage operations in ports. A thorough examination of the findings reveals that the 'Requirement for an Emergency Response Unit' (0.2835715) criterion is assigned the highest weighting value. This finding suggests that port operators prioritise the capacity to respond promptly and efficiently to accidents that may occur during dangerous goods operations as the most critical factor. In particular, the necessity of a robust response capacity in high-risk incidents, such as fires, explosions or chemical leaks, has been identified as a fundamental requirement for ensuring operational safety.

The second most significant criterion was identified as Storage Area Security (0.203924). This finding indicates that the safe storage of dangerous goods within the port area and their protection through appropriate physical security measures are of high priority for port authorities. The establishment of secure storage areas is of critical importance not only in terms of operational efficiency but also in minimising risks to the environment and human health.

When examining other criteria, such as Authorised Personnel Access (0.141919), Dedicated Operational Area for Dangerous Goods Storage Areas (0.1346105), Storage Area Communication (0.1199805) and Storage Area for Specific Dangerous Goods (0.1159945), it is evident that these have relatively lower weight values. Nevertheless, it is widely acknowledged that these criteria are complementary elements that support the effective and safe conduct of dangerous goods operations. It is imperative to acknowledge the pivotal function of effective communication systems in facilitating coordination during emergency situations.

The findings indicate that port operators have adopted a risk management and safety-focused approach to dangerous goods container storage activities. The fact that safety and emergency response capacity emerged as priority criteria in the AHP analysis demonstrates that dangerous goods operations are treated not merely as a logistical activity, but also as a comprehensive safety management process. In this context, the enhancement of safety infrastructure and the augmentation of emergency response capacity are of paramount importance in the planning and management of dangerous goods storage operations at ports.

6. CONCLUSION

The present study sought to analyse the operational approaches of container terminals in Türkiye with regard to the storage of dangerous goods containers. This was achieved by identifying and prioritising critical safety-related criteria. A comprehensive review of the extant literature was undertaken, and six principal criteria were identified. These were then subjected to evaluation through the Analytic Hierarchy Process (AHP). The data obtained from twenty container terminals was analysed using the SuperDecisions software in order to ascertain the relative importance of each criterion in the context of dangerous goods storage operations.

The findings indicate that the necessity for an emergency response unit is the most significant factor influencing dangerous goods storage operations. This outcome is indicative of the inherently high-risk nature of hazardous materials, where incidents such as fires, explosions, chemical leaks or toxic gas releases have the potential to rapidly escalate and lead to significant environmental, economic and operational consequences. Consequently, the capacity to respond expeditiously and efficaciously to emergency situations constitutes a pivotal element of port safety management systems.

The second most significant criterion identified in the analysis is that of storage area safety, which encompasses structural and technical safety measures implemented within the storage environment. These measures encompass the implementation of fire detection and suppression systems, ensuring proper ventilation, the segregation of incompatible substances, the utilisation of impermeable ground structures, and the installation of physical barriers. Such preventive mechanisms are essential for reducing the probability of incidents occurring in the first place and constitute a fundamental layer of risk mitigation in hazardous cargo operations.

The results of the study also indicate that authorised personnel access and communication systems play an important role in ensuring operational safety. The implementation of effective access control measures is instrumental in mitigating the risk of untrained personnel exposure to hazardous environments. The establishment of robust communication systems is pivotal in fostering coordination among operational teams and emergency response units. In complex port environments where multiple actors interact simultaneously, communication resilience becomes a critical factor for maintaining situational awareness and ensuring coordinated responses during abnormal events.

In contrast, dedicated storage areas and designated operational areas were found to have relatively lower priority levels compared to other criteria. While these elements contribute to safer operational planning and spatial organisation, they primarily serve as supporting components rather than primary risk mitigation mechanisms within the overall safety architecture. This finding suggests that port managers tend to prioritise dynamic risk control and emergency preparedness capabilities over purely spatial or organisational arrangements.

The results demonstrate that dangerous goods storage operations in ports are managed within a multi-layered safety management framework consisting of preventive, control and response-oriented mechanisms. The prioritisation pattern observed in this study reflects a hierarchical safety structure, in which emergency preparedness and structural safety measures form the core of risk mitigation strategies, supported by organisational and communication-based controls.

From a pragmatic standpoint, the results of this study offer several significant ramifications for port administrators and policymakers. Firstly, investments in emergency response capacity, including specialised response units, training programmes and regular emergency drills, should be prioritised in order to enhance operational resilience. Secondly, it is recommended that port authorities continue to strengthen technical safety infrastructure within storage areas through the implementation of advanced detection systems, automated monitoring technologies and improved hazard segregation practices. Thirdly, the integration of digital communication and monitoring systems, including sensor networks, real-time tracking technologies and decision-support platforms, has the potential to significantly improve situational awareness and coordination during hazardous cargo operations.

Furthermore, enhanced institutional coordination between port authorities, emergency services and regulatory agencies has the potential to further bolster preparedness and response capabilities in the event of hazardous material incidents. The establishment of shared communication protocols and joint emergency response exercises has the potential to enhance operational readiness and reduce response times in crisis situations.

Notwithstanding the contributions of the present study, there are several limitations that must be acknowledged. The analysis focuses on container terminals operating in Türkiye and relies on expert evaluations obtained from a limited number of ports. Future research could expand the scope of the analysis by incorporating international port comparisons, larger datasets and additional safety indicators such as environmental risk factors, technological monitoring systems and regulatory compliance measures. Furthermore, the integration of other multi-criteria decision-making approaches, such as Fuzzy AHP, DEMATEL or ANP, has the potential to provide a more profound understanding of the interrelationships between different safety criteria.

In conclusion, the study emphasises that effective management of dangerous goods container storage operations necessitates a comprehensive safety-oriented approach that integrates preventive infrastructure, operational control mechanisms and robust emergency response capabilities. It is imperative to simultaneously reinforce these elements to enhance port safety performance and ensure the sustainable management of hazardous cargo operations within increasingly intricate maritime logistics systems.

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