Research on Evaluation Indicators for Maritime Firefighting Capabilities

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Abstract. As a prominent maritime and shipping power, our nation is actively engaged in the development of a formidable maritime and transportation infrastructure. The enactment of the "Maritime Silk Road" strategy, coupled with the growing expansion of maritime transport, necessitates the urgent formation of a commensurate maritime firefighting force to elevate readiness against significant emergent incidents at sea. The construction of evaluative indicators for maritime firefighting capabilities is crucial in advancing these capabilities further. This advancement is pivotal for enhancing service to national strategies, preserving national sovereignty and maritime security, and for engaging deeply in the governance of global maritime affairs.

1. Introduction

Maritime firefighting refers to the specialized rescue operations conducted in a marine environment in response to emergencies such as fires, explosions, and collisions on vessels, offshore platforms, or coastal facilities. These activities encompass, but are not limited to, fire control and extinguishment, personnel evacuation and search and rescue, medical aid, hazardous material management, and environmental protection. Maritime firefighting is a multifaceted domain that encompasses a wide range of techniques and strategies, playing a critical role in ensuring the safety of individuals, property conservation, environmental stewardship, public security maintenance, and supporting national strategic objectives.

The Ministry of Transport's Rescue and Salvage System, an integral component of the national emergency response system, serves as China's professional maritime firefighting and rescue force. Since its establishment in 1951, it has been responsible for emergency responses to maritime incidents within Chinese waters, lifesaving, vessel and property salvaging, maritime firefighting, sunken ship and object recovery, oil spill cleanups, and other public welfare duties aimed at ensuring the safety of maritime transportation and the development of maritime resources.

Over 90% of China's international trade is conducted via maritime transport, and with the accelerated integration of sea, land, and air transport networks, the frequency of related maritime activities has increased. This rise leads to higher risks of mass emergency rescues, ship collision conflagrations, and other major sudden maritime incidents, thereby setting more stringent requirements for comprehensive maritime firefighting and rescue infrastructure, base deployment, and the professional qualifications of firefighting personnel. In this context, scientifically establishing evaluative indicators and objectively assessing the developmental level of maritime firefighting capabilities holds significant importance. Such measures are essential to enhance maritime firefighting abilities, support the nation's strategic deployments, address complex maritime firefighting security situations, deeply engage in and lead the construction of a global waterborne traffic safety and emergency governance system, meet the people's aspirations for a better life, and ensure that the salvage system plays a pivotal role during critical moments.

2. Current Development and Issues of Maritime Firefighting Forces

2.1. Current Development Status

The Salvage System under the Ministry of Transport, after several adjustments, currently comprises the North Sea, East Sea, and South Sea Rescue Bureaus; the Yantai, Shanghai, and Guangzhou Salvage Bureaus; and five affiliated rescue aviation teams: the North Sea First, East Sea First and Second, and South Sea First and Second Rescue Aviation Teams, creating a relatively complete salvage network along China's coastal areas. This has established a tripartite force structure consisting of rescue teams, salvage fleets, and aviation teams.

2.1.1 Personnel Structure

The current salvage system employs 6,267 personnel. Of these, the rescue system's maritime staff includes 1,305 individuals (785 senior crew members, 376 ordinary
crew members, and 144 divers), while the salvage system's maritime personnel number 2,095 (1,447 senior crew members, 407 ordinary crew members, and 241 divers), accounting for 65.5% and 57.1% of the total numbers in the rescue and salvage systems, respectively.

2.1.2 Technical Equipment

The three rescue bureaus have a total of 73 rescue vessels, including three 14,000KW vessels, two 12,000KW vessels, twenty-two 8,000KW vessels, three 6,000KW vessels, and one 4,000KW vessel. All are capable of deploying 24 hours a day in sea conditions up to Beaufort scale 9 (wave height of 14 meters, wind force 12) and conducting effective rescue operations in sea conditions up to Beaufort scale 6 (wave height of 6 meters, wind force 9). The rescue vessels are equipped with firefighting monitors, with the highest reach up to 190 meters and a maximum flow rate of 1,800m³/h. Specifically, the 6,000KW and 8,000KW offshore rescue vessels possess primary firefighting capabilities with a capacity of 21,200 cubic meters per hour, while the 14,000KW rescue vessels have secondary firefighting capabilities with a capacity of 41,800 cubic meters per hour.

2.1.3 Emergency Support Capacity

Currently, the three rescue bureaus (including the five rescue aviation teams) have established 25 rescue bases (including advanced rescue stations) and eight rescue aviation bases along the coast, which essentially constitute an integrated land-sea-air rescue network, allowing for coordinated response and mutual support.

2.2. Existing Problems

2.2.1 Shortage of Professional Maritime Firefighting Personnel

Firstly, there is a lack of skilled maritime firefighting emergency rescue commanders and management talent, and a professionalized, specialized, and modern maritime firefighting force structure has yet to be established. Secondly, due to the high risk and intensity of maritime fire suppression and other emergency rescues, coupled with low compensation, there is a significant attrition of frontline personnel. Thirdly, there is an urgent need to enhance the construction of maritime firefighting and hazardous chemical emergency response teams for challenging rescues such as ship fires and hazardous chemical disposal.

2.2.2 Equipment Capability Building Needs Further Strengthening

Firstly, the structure of maritime firefighting vessels needs optimization, with uncoordinated development and allocation among large, medium, and small-sized rescue ships (boats); there is an insufficient number of heavy-duty rescue vessels to meet the emergency rescue demands of maritime firefighting and other accidents at sea. Secondly, aerial rescue capabilities are inadequate, with aircraft configurations requiring further optimization and communication information abilities between aircraft and ships needing improvement. Thirdly, there is an urgent need to introduce shipboard detection and personal protective equipment, as there is a lack of highly specialized maritime firefighting and advanced personal safety protective gear, particularly for hazardous chemical protection.

2.2.3 Maritime Firefighting Preparedness and Emergency Response Capabilities Need Improvement

There is a lack of systematic research on emergency response techniques and measures for incidents including fires involving ship-borne oil and hazardous chemicals. The emergency response techniques and operational guidelines for shipborne oil and hazardous chemical fire accidents are incomplete. Additionally, emergency rescue capabilities in adverse weather and sea conditions are inadequate, and there is a particular weakness in rapid search and location of individuals in complex conditions and nighttime search and rescue responsiveness.

2.2.4 Enhancement of Training for Maritime Firefighting Personnel is Necessary

Firstly, individuals engaged in maritime firefighting operations lack specialized training in maritime fire suppression. Currently, the primary personnel involved in combating shipboard fires include salvage crew members, divers, rescue pilots, and water rescue specialists. These individuals are deficient in specialized knowledge and skills training specific to maritime firefighting. Secondly, there is an inadequacy of training facilities for maritime firefighting, leading to a shortfall in practical and tactical training for personnel involved in maritime fire suppression operations.

3. New Situations and Requirements in Maritime Firefighting

3.1. Challenges Brought by Globalization

With the growth of global trade, the increasing size of ships and the expansion of shipping routes have led to more complex challenges in maritime firefighting. Large vessels such as mega oil tankers and container ships require more sophisticated and robust firefighting facilities and strategies in the event of a fire.

3.2. Application of Advanced Technologies

Modern maritime firefighting increasingly employs high-tech methods, including drone reconnaissance, high-precision positioning systems, and remote-
controlled firefighting equipment. These technologies provide safer options for assessing and responding to fires, especially in hazardous environments, demanding faster times and greater efficiency in fire response and management.

3.3. Advanced Ship Design and New Materials

Modern ships, particularly cruise liners and container ships, are becoming larger and more complex, presenting challenges in terms of compartmentalization, accessibility, and ventilation systems. The use of new materials in shipbuilding, such as composite materials and high-strength lightweight alloys, shows different behaviors under fire conditions compared to traditional materials, necessitating new firefighting strategies and methods.

3.4. Increased Environmental Considerations

With heightened global focus on environmental protection, maritime firefighting must also consider its impact on marine environments, especially in sensitive ecosystems. The environmental friendliness of firefighting foams and chemical extinguishing agents is a significant consideration.

3.5. Firefighting Requirements for Special Vessels

Special types of vessels, such as Liquefied Natural Gas (LNG) carriers and chemical ships, have more stringent firefighting requirements than traditional cargo ships. The cargoes carried by these vessels are highly flammable and explosive, increasing the complexity of firefighting and rescue operations.

3.6. Specialized Training for Firefighting Personnel

Maritime firefighting personnel require more specialized and systematic training to address increasingly complex fire scenarios. This encompasses the utilization of virtual reality technology for simulated environments, employing wearable sensor devices for analytical monitoring of firefighters' activities[1,2,3], operational training on new firefighting equipment, and skill development for managing unique types of fires.

3.7. International Cooperation and Standardization

With the increasing frequency of maritime activities, there is a growing need for international cooperation and standardization in maritime firefighting. Actively participating in international maritime and salvage organizations' work, under the strict compliance with relevant international conventions, is essential to maintain global livelihood and safety channels. Deepening cooperation with other countries in the technical field of maritime firefighting equipment and promoting mutual assistance, information sharing, personnel exchange, training, and joint exercises in maritime firefighting and emergency rescue are crucial. This approach enriches the content of international cooperation and builds an international joint action force in maritime firefighting.

4. Strategies for Enhancing Maritime Firefighting Capabilities

In service to the nation's major strategic deployments such as building a strong transportation and maritime country and jointly constructing the "Belt and Road" initiative, and with the aim of meeting the demand for maritime emergency salvage and firefighting, priority is given to improving the construction of nearshore and offshore maritime firefighting and rescue capabilities. Efforts are focused on strengthening the construction of maritime firefighting equipment and resource allocation, enhancing the development of professional maritime firefighting personnel, strengthening the reserve and supply system of maritime firefighting materials, perfecting maritime firefighting emergency plans and response procedures. Adapting to the national economic and social development and strategic needs of a powerful transportation country, effective safeguards are provided for maritime human life and environmental safety.

5. Construction of Evaluation Indicators

The typical methodologies for fire service assessment include checklist approaches, fault tree analysis, event counting analysis, and preliminary analysis methods[4]. However, there is no unified standard method for evaluating maritime firefighting capabilities. This paper selects five key dimensions, as shown in Table 1, influencing maritime firefighting effectiveness and comprehensively constructs an evaluation system for maritime firefighting capabilities.

5.1. Maritime Firefighting Response Time

The response time indicator evaluates the duration it takes for a maritime firefighting team to respond from receiving an alarm to arriving at the scene, including core indicators such as alarm reception and confirmation time, dispatch and mobilization time, travel time, and time to commence operations upon arrival. By constructing a maritime firefighting response time model, this provides a quantitative method for each phase from the occurrence of a fire incident to the start of firefighting operations, identifies time bottlenecks in the maritime firefighting process, optimizes resource allocation, reduces potential damage, and improves the overall efficiency and effectiveness of the response.

The maritime firefighting response time model is as follows:

\[ T_r = T_a + T_d + T_t + T_i \]  

where:
5.4. Maritime Firefighting Cost Efficiency

The cost efficiency indicator measures the relationship between resource consumption and rescue outcomes during maritime firefighting missions, including core indicators such as the effectiveness of firefighting operations, resource consumption, personnel involvement, time cost, equipment depreciation, and maintenance costs. By constructing a maritime firefighting cost efficiency model and analyzing empirical data on resource consumption and the effects of historical firefighting operations, this allows for the quantification and evaluation of resource usage and the identification of key variables impacting cost efficiency, thereby achieving more effective resource management and better rescue outcomes in future operations.

The maritime firefighting cost efficiency model is:

$$ C_e = \frac{O}{R + S + T + E} $$

where:

- $C_e$ is the firefighting rescue cost efficiency;
- $O$ is the effectiveness of rescue operations, e.g., the area of the fire controlled or number of people rescued;
- $R$ is resource consumption (such as fuel, firefighting materials, etc.);
- $S$ is personnel investment (including firefighting rescue personnel and logistical support);
- $T$ is the time cost;
- $E$ is equipment depreciation and maintenance cost.

5.5. Maritime Firefighting Risk

Maritime Firefighting Risk Assessment Indicators are employed to evaluate the risk levels associated with conducting maritime firefighting and rescue operations. These primarily include the likelihood of various risks occurring and the potential severity of consequences arising from these risks. Analyzing and summarizing the risks of different maritime incidents is crucial in constructing maritime firefighting risk assessment indicators. This process aids in identifying key factors contributing to maritime incident risks and in proposing risk control measures. Common methods for analyzing maritime incident risks include Bayesian networks, complex network analysis, and N-K models[5-8]. In practice, the analysis of the $i$th type of maritime firefighting risk can employ one or more of these methods. By developing a maritime firefighting risk assessment model, historical accident reports, case studies, and risk checklists are analyzed to identify potential risks. This includes assessing their likelihood of occurrence and predicting their consequences, thereby facilitating the establishment of appropriate preventive measures and response plans during firefighting and rescue operations.

The maritime firefighting risk assessment model is:

$$ R = \sum H_i F_i $$

where:

$H_i$ is the probability of an event occurring and $F_i$ is the consequence of such an event.
R is the overall risk;  
$H_i$ is the probability of the (ith) risk occurring;  
$F_i$ is the severity of consequences if that risk were to occur.

**Table 1. Construction of Evaluation Indicators**

<table>
<thead>
<tr>
<th>Evaluation Dimension</th>
<th>Core Indicators</th>
<th>Other Indicators</th>
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<tbody>
<tr>
<td><strong>Maritime Firefighting Response Time</strong></td>
<td>Alarm reception and confirmation time, Dispatch and mobilization time, Travel time, Time to commence operations upon arrival.</td>
<td>Maritime route distance, Speed of firefighting rescue vessels.</td>
</tr>
<tr>
<td><strong>Maritime Firefighting Resource Allocation</strong></td>
<td>Probability of fire occurrences in different regions, Coverage coefficients of firefighting resources in different regions.</td>
<td>Range of resource coverage, Number of firefighting facilities, Number of firefighting personnel.</td>
</tr>
<tr>
<td><strong>Maritime Firefighting Rescue Success Rate</strong></td>
<td>Resource sufficiency, Rescue team experience and capabilities, Condition of distressed vessels, Weather and sea conditions.</td>
<td>Number of vessels, Quantity of firefighting rescue equipment, Magnitude of the fire on the distressed vessel, Complexity of the structure of the distressed vessel.</td>
</tr>
<tr>
<td><strong>Maritime Firefighting Cost Efficiency</strong></td>
<td>Effectiveness of firefighting rescue operations, Resource consumption, Personnel involvement, Time cost, Equipment depreciation, Maintenance costs.</td>
<td>Quantity of fuel and firefighting materials used, Number of personnel involved in firefighting rescue and logistics support.</td>
</tr>
<tr>
<td><strong>Maritime Firefighting Risk</strong></td>
<td>Probability of different risks occurring, Severity of consequences if those risks were to occur.</td>
<td>Meteorological and oceanographic conditions, Equipment failure risk, Communication disruption risk, Hazardous chemical leakage risk.</td>
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### 6. Conclusions

In academic terms, the evaluation of maritime firefighting capabilities, particularly for a specific organization's proficiency and efficiency in maritime firefighting and rescue operations, necessitates a quantitative analysis of key indicators. This evaluation framework, comprising response time, resource allocation efficiency, rescue success rate, operational cost-effectiveness, and maritime firefighting risk, is generally applicable. However, its limitations must be acknowledged in specific contexts: first, under extreme weather conditions, such as strong winds, high waves, or dense fog, which may impact the accuracy of the evaluation system; second, in deep-sea incidents far from land, where extended response times are not fully reflected in the evaluation; and third, for large or special vessels like mega tankers, where the system might not fully encompass unique risks and response strategies. Maritime firefighting is a complex and specialized field, merging advanced technologies and diverse strategies to address maritime emergencies. To achieve this quantitative evaluation, it's crucial to focus on the collection and updating of real-time data, using sources such as Automatic Identification Systems (AIS), navigational logs, and accident reports for comprehensive data gathering, analysis, and validation. Moreover, the evaluation model should develop complex and varied emergency scenarios based on specific situations, including extreme weather, deep-sea rescue, and special vessel rescue, to address a broader range of potential maritime incidents. Finally, adaptation to emerging technological developments is crucial. As maritime firefighting technologies continue to advance, the evaluation indicators should be continually optimized and refined to remain relevant and effective.

### References