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A framework for using computational fire simulations in the early phases of ship design

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ABSTRACT

Fires on ships spread rapidly and are difficult to control. Both passengers and some ship crew maybe unfamiliar with real fire situations. Mismanagement or a delayed preliminary response can yield fatal damage to a ship, including the loss of lives. Despite all ships being built in accordance with to fire safety rules and regulations, ship fire accidents still occur. Currently, computational simulation tools are used to predict and mitigate fire propagation during the ship design process. Dynamic fire simulations can assist better appreciation of heat and smoke tendencies and behavior based on cause, location and environmental conditions. Moreover, ship designers can apply fire control options, such as fume-tight doors, sprinklers, water mist while giving due consideration for improved survivability. However, fires have no reproducibility, and many types of equipment and facilities cannot be considered in such simulations. In addition, applying the simulation is sometimes difficult because the design process is typically limited by budget and time constraints. Numerous fire scenarios are required for accurate simulations. Vague and varying simulation requirements can confuse ship designers. Consistently decreasing design freedom and major design revision requirements can cause projects to fail. Therefore, a framework for using computational fire simulations during the early phases of ship design was explored in this study. This work is focused on how to arrange fire control options with minimal changes of existing design procedures.

1. Introduction

Every ship is equipped with appropriate fire fighting and evacuation equipment and facilities that follow the International Maritime Organization (IMO) safety of life at sea (SOLAS) requirements and rules for classification. Although every ship is equipped with various fire fighting systems as per these requirements, ship fires continue to occur. A ship fire can spread rapidly and is difficult to extinguish due to complicated internal structure, short line-of-sight, dark interior, rapid heat transfer via the steel structure and toxic smoke. To improve survivability in the event of a fire/smoke incident, modern vessels are equipped with an effective incident management system with dynamic kill-cards and a smart vision system. (Shafie-pour et al., 2012). Nevertheless, once a fire occurs, the preliminary countermeasures are important to ensure that enough time is available to prevent the fire from spreading and allow egress (Hakkarainen et al., 2009). Fig. 1 shows examples of ship fire accidents.

When considering fires in a ship design, dispersion of heat and smoke should be considered first; then, structural collapse and equipment and functional failures can examined. Ships that lack a modern damage control system (DCS) incorporating effective fire/smoke detection and an incident management system (IMS) (Reza Shafie-pour and Sajdak, 2015) and insufficient onboard fire fighting equipment, are vulnerable to fires. Therefore, appropriate ship design for fire safety is important. Moreover, repetitive onboard fire fighting and abandon ship drills linked to fire safety management during a ship's life cycle are also important (Kang et al., 2013; McDonald et al., 2002). A large number of ship fire data are required for safe ship design via computational simulations and experimental combustion tests. However, every ship design is limited by both budget and time. In addition, fire simulation and experimental test data are difficult to obtain during the early phases of ship design. A ship design project may fail if the simulation or test results require major design changes in the later phases of ship design. The arrangement of rooms, corridors, doors and other openings is important for ensuring escape routes and preventing a fire from spreading, as it is important to consider all required sensors for survivability improvement under fire/smoke incidents. Appropriate extinguisher specifications, numbers and nozzles arrangements should be determined before issuing a purchase order request (POR) for equipment and facilities. A practical framework for computational fire

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Fig. 1. Ship fire examples (www.cruiselawnews.com and www.fortunes-de-mer.com).

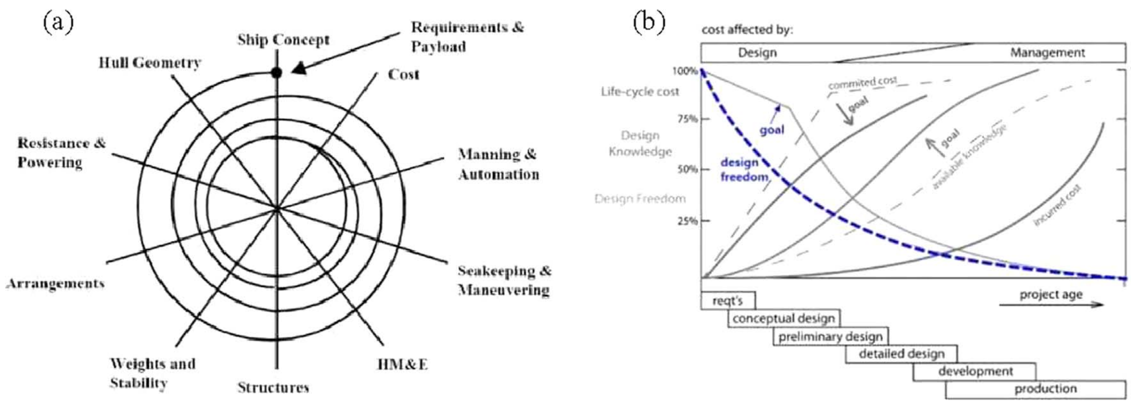


Fig. 2. Example of (a) design spiral and (b) design freedom (Clifford et al., 2000; Verhagena et al., 2012).

simulations, based on the limited available data in the early phases of ship design is required to prevent major design changes during later design phases.

2. Ship design process and computational fire simulation

Generally, ship designs follow the design spiral portrayed in Fig. 2(a). Moreover, design freedom decreases with increasing (see Fig. 2(b)). Because major design changes in later design phases are not allowable, fire safety issues should be considered during early design phases, which typically lack sufficient design data, and are then gradually solidified as the design process moves forward.

Although every ship follows empirical fire safety rules and regulations, there are still rooms to enhance fire safety within existing rules and regulations. Model based fire safety design is one example. Dracos Vassalos (2009) suggested the fire risk model outlined below:

$$Risk_{firezone} = \sum_{i=1}^{fz} \Delta Risk_i, \tag{1}$$

$$\Delta Risk_i = f(i) Pi(Ef) E[N], \tag{2}$$

where

$f(i)$: frequency of fire ignition event in space i;
$Pi(Ef)$: fire escalation from its origin; and
$E[N]$: loss of human life injuries/fatalities.

In an extended study, for the risk modeling, many improved features were proposed by Papanikolaou (2009), Guedes and Teixeira (2001), Wang (2002), Konovessis and Vassalos (2008) and Vanem and Ellis (2010). However, risk modeling for fire safety is still unfamiliar and a challenge for ship designers. The lack of historical data complicates the use of such risk models. Expert opinions in related fields sometime conflict with the results of these models. Though an appropriate risk modeling process is essential for safe ship design, in other to enhance fire safety in the early design phase, a practical and easier method is required for the stakeholders of ship design. In addition the high cost to model real ship fires or scaled mock-up tests suggests that computational fire simulations should be used during ship design. Since fires have no reproducibility, and computational simulations cannot reflect every inflammable material within a real ship. Therefore, the spread of smoke and heat in computational simulations is not quantitative; instead, the simulations suggest time related smoke and heat dispersion tendencies in certain arrangement of zones, corridors, doors, hatches, sprinklers, water mist and so on. For consideration of fire safety during ship design, the IMO established the IMO MSC Circulation 1002 “Alternative design and arrangements process” in 2001 (IMO, 2001), which is adoptable for alternative designs and arrangements. The fire safety engineering processes (FSEs) from ISO TC 92/SC 4/WG 10 N55Rev4, which are shown in Fig. 3, should also be considered (Hietaniemi et al., 2007).

3. Computational fire simulation framework for ship design

Significant specific ship design data are needed to design a ship following alternative design and arrangements or FSE design processes. However, little data are available during the early phases of ship design. Moreover, existing ship design processes for shipyards are difficult to change because hundreds of stakeholders are involved. Budget and time limitations should also be considered. As a ship design becomes concretized along the ship design spiral, a phased acquisition of ship design data for fire safety design measures is needed.

During the conceptual design phase, area classification and fire modeling are applicable. During the preliminary basic design phase, numerous alternative arrangements are generated. The rate at which heat and smoke dispersion, and fire fighting accessibility and egress for each compartment, including doors and other openings, can be compared. Equipment and facilities are arranged during the basic design phase. To mitigate fires, fire extinguisher specifications, numbers and nozzles, and nozzle arrangements are determined. During this

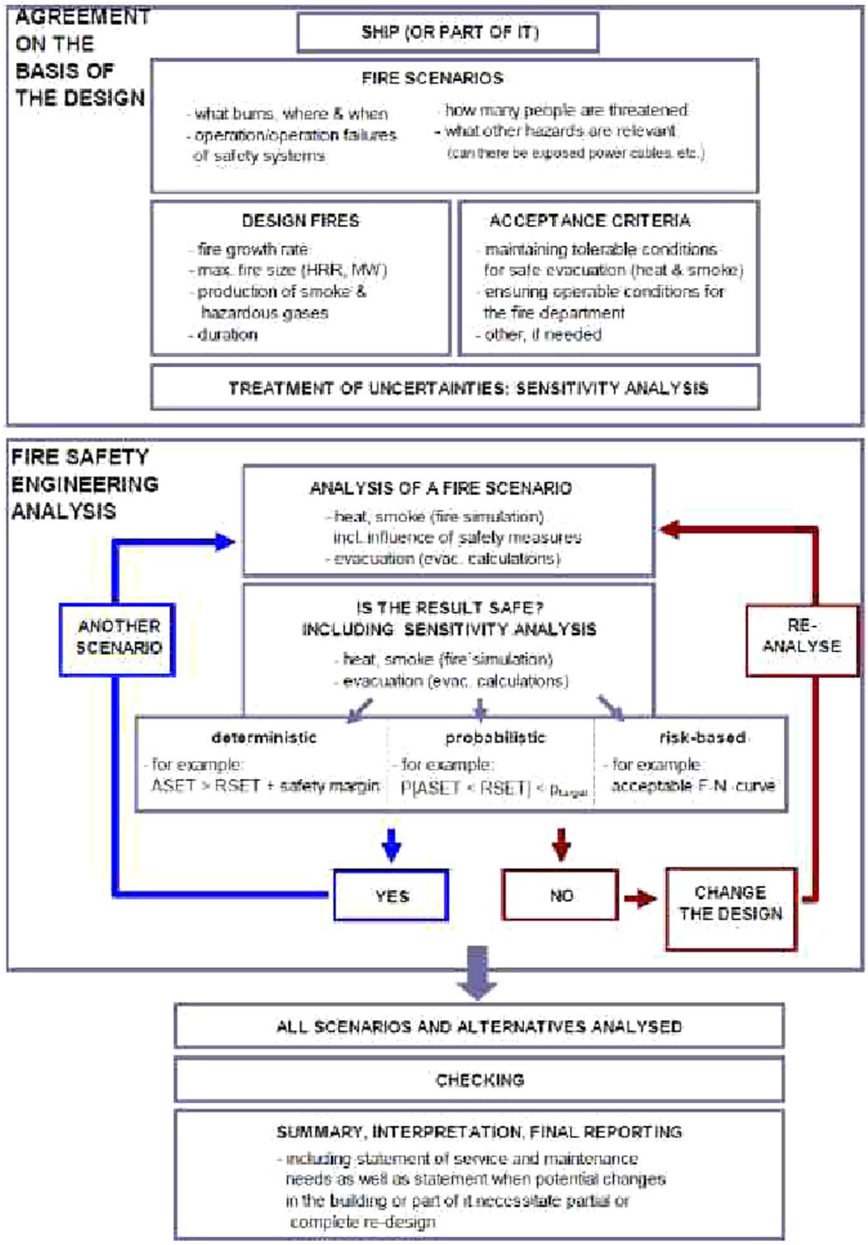


Fig. 3. Fire safety engineering (FSE) design process scheme (ASET=available safe egress time; RSET=required safe egression time) (Hietaniemi et al., 2007).

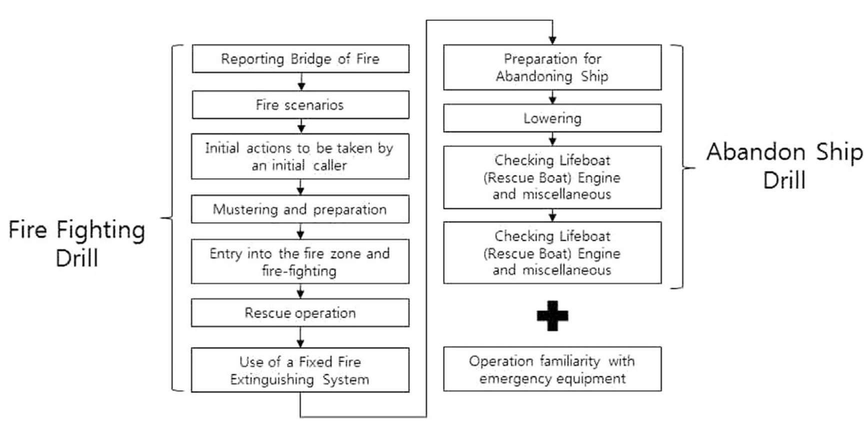


Fig. 4. Fire fighting/abandon ship drill procedures (Korea Resister of Shipping, 2009).

phase, each design alternative's performance can be compared. Computational fire simulation results can be considered to create a fire safety plan. Fire simulations can establish timely planned entry and evacuation standards, operating parameters and fire fighting protocols. For example, a fixed CO_2 fire-extinguishing system will activate 30 s after an alarm is signaled in a machinery room. In that situation, all of the crew, including the fire fighting team, should evacuate the machinery room. However, to maintain key ship functions, some workers may be forced to remain in the room if other means of remote control and monitoring, such as the use of laptops, are not available. Effectively controlling a fire while maintaining crew safety and ship functions are the main elements of fire safety plans. Moreover, a ship's fire safety plan should be adjusted throughout her life cycle via onboard training. During a ship's life cycle, all computational fire simulation results can be used to create a decision-making aid. The fire simulation data can be used to predict heat and smoke dispersion and determine fire fighting and evacuation times. Fig. 4 shows general fire fighting and abandon ship drill procedures that should be considered for fire safety planning during various phases of ship design (KRS 2009).

A computational framework for fire simulations should be organized within the bounds of existing rules and regulations and should not result in substantial changes in the existing ship design process to avoid excessive cost and time.

While Fig. 3 describes fire safety engineering (FSE) design process scheme from ISO TC 92/SC4/WG10 N55 Rev4, the design process of Fig. 3 should consider onboard fire fighting procedures of Fig. 4. From this viewpoint, a framework for a ship design process that considers an existing FSE design procedures scheme and onboard fire fighting drill procesdures, concurrently, is required. Therefore, existing considerations for ship design and building should be applied to the framework. Fig. 5 shows an alternative design and arrangement process, formal safety assessment procedures, and a ship design and building process in the shipyards that should be considered when constructing a computational fire simulation framework.

The considerations shown in Figs. 3–5 yield the computational ship fire simulation framework portrayed in Fig. 6. This framework follows existing ship design processes and is appropriate for adopting fire simulations using increasing data availability. The framework is also within the bounds of international frameworks, such as alternative design and arrangement processes and formal safety assessment. For arrangement of rooms, corridors, doors, and other openings, target zones for computational fire simulation should be selected in the early design phase. In that case, without concretized risk model, historic data and other similar ship types' risk model (or experts' advice) can be considered. After that, the risk model can be concertized by using detailed ship design data basis precision estimation for fire escalation and loss of human life injuries/fatalities. Safety evaluation of design result considers comparative safety level of each design result in the boundary of deterministic, probabilistic and risk-based allowable safety level of Fig. 3.

4. Application

To determine the usability of the suggested framework, a Ro-Pax (Roll-On-Roll-Off-Passenger-ship/ferry) design procedure was assumed. The ship specifications are shown in Table 1.

4.1. Conceptual design phase

During the conceptual design phase, as the required data for design fire and combustible materials for fire simulation are insufficient, target areas for fire simulation are selected based on historical fire accident data as shown in Fig. 7(a); thus, fire scenarios are considered, as shown in Fig. 7(b), rather than a formal risk modeling process. To minimize the consequence of a risk, time-related smoke and heat dispersion tendency results from fire simulations are examined for appropriate arrangement of doors and other openings including fire fighting systems. These simulation results are important for designing air inlets and outlets for the ventilation systems, including doors and openings, and determining a proper location for the internal combustion engines

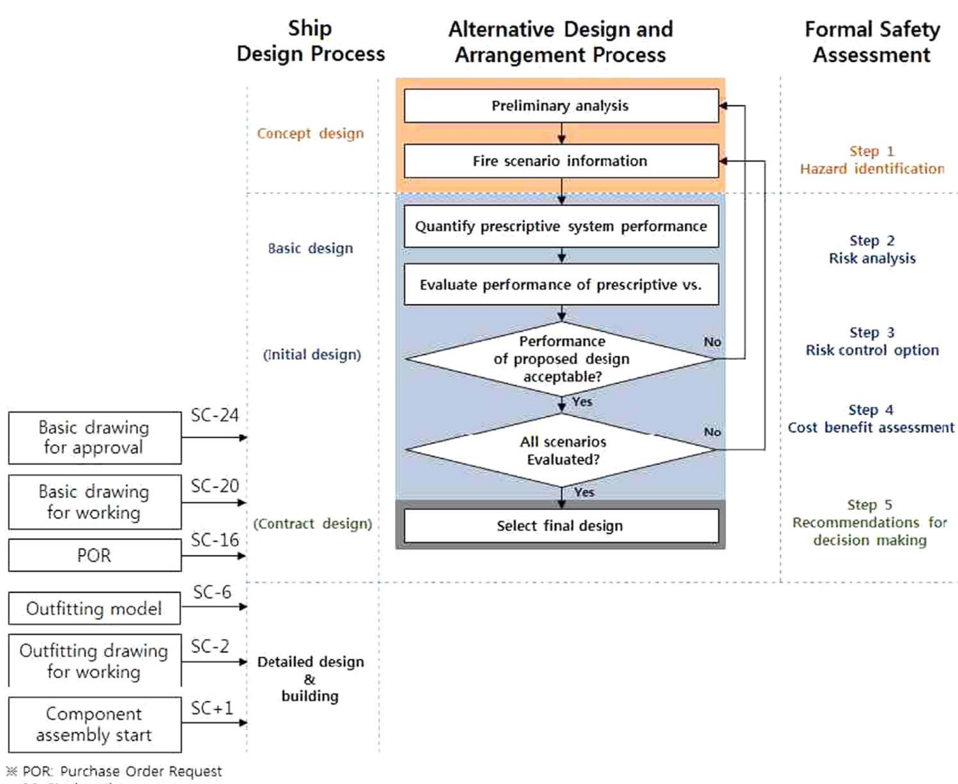


Fig. 5. Considerations for a computational ship fire simulation framework.

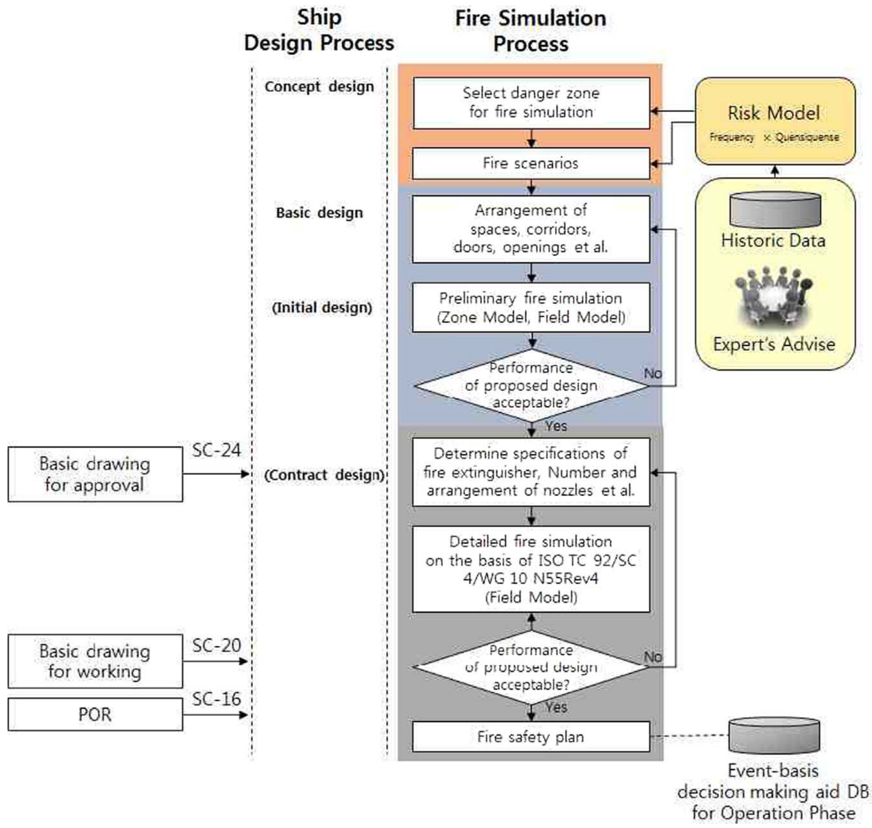


Fig. 6. Computational ship fire simulation framework.

Table 1
Required specifications for Ro-Pax ship design.

Deck length (m)	155 m
Deck width (m)	28 m
Number of decks	2
Number of cabins	300
Number of staircases	5 (4 of 2 m width, 1 of 4 m width)
Number of guests	450
Guest type	International maritime organization ship passenger

and other fire equipment. Fig. 7 shows example historical fire data and risk modeling procedures.

A typical ship can be categorized into the following main areas: machinery room, living space, cargo space, galley and distribution. In this study, the machinery room was selected for a case study. The considered design fire scenarios are shown in Table 2.

In this paper, for the fire simulation application, proven open-source software such as CFAST (Consolidated model of Fire Growth And Smoke Transport) for zone model and FDS (Fire Dynamics Simulator) for computational fluid dynamics codes, were adopted (Floyd, 2002). Because the Ro-Pax was considered an application example ship, explosion and other sources of fire, such as missile and torpedo hits are not considered.

Table 2
Factors for the design fire scenarios.

Factor	Value	References
Fire object	Oil-mist, over heated	NFPA 101
Door	Open, closed	General arrangement
Windows	Open, closed	General arrangement
Detection	Success, fail	Sensors
Initial reaction	Success, fail	Control system activation
Fire suppression	Success, fail	Crew egress, control system activation

4.2. Preliminary basic design phase

The preliminary basic design phase generates numerous design

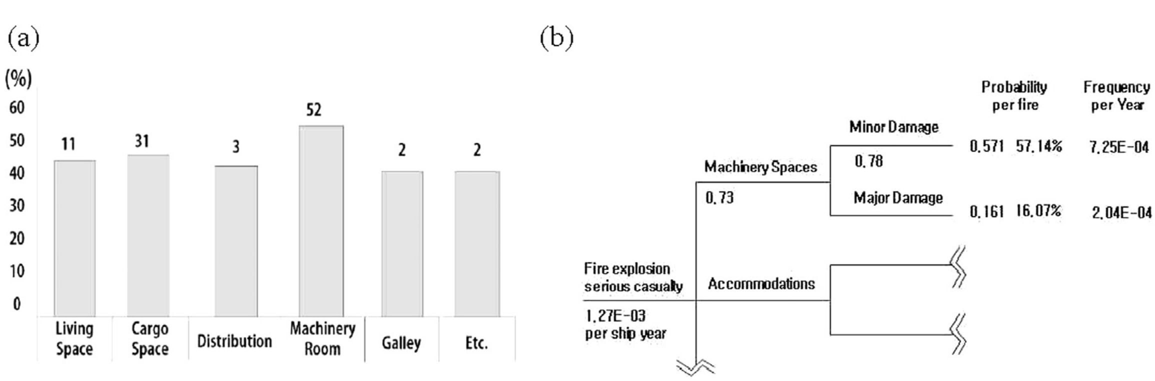


Fig. 7. Examples of (a) historic data (www.mpss.go.kr); (b) fire scenarios (derived from ⟨http://gisis.imo.org⟩).

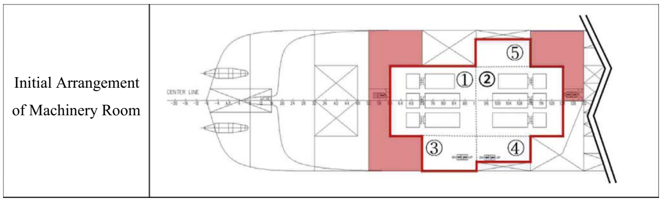


Fig. 8. Example of designing a galley and machinery room.

alternatives for arranging spaces, corridors, doors, and openings. Preliminary fire simulations can be used to select the safest design. Because no detailed data exist for inflammable materials in these spaces, their layout, including doors and openings, are evaluated based on accessibility and the spread of both heat and smoke. A zone model was adopted only as a rapid heat and smoke spread tendency check. Zone models are easy for designers to use and faster than field models. A relative comparison of the results helps determine the proper layout for rooms, corridors, doors and openings. Fig. 8 shows a machinery room design. The shaded areas in the drawing are adjacent danger zones that should be jointly considered during fire simulations.

For fire simulations, a design fire should be generated; references such as NFPA 101 are often available for this purpose. And designers use their own fire model which delivered form specific experiments or ship owners. For fire simulations, areas are defined according to the following progression: area selection, three-dimensional structure setup, finish applications and door and opening setup. For design fire, the inflammable materials, ignition location, combustion heat and gasification, and area (length and width) should be defined. The design fire was assumed to be a 1 mm fuel depth diesel oil pool fire with a heat of combustion value of 34 MJ/ m^2.

In case of machinery room design, wider area is good for effective maintenance but vulnerable for fire accident. With assumption that fire accident happens in this place, designer should arrange doors and openings with considering of fire safety. Concurrently, the arrangement should meet the requirement of damage stability which considering flooding into the machinery room. As shown in Fig. 9(a), steel bulkhead between rooms is not good for fire safety since linked accesses become hot concurrently. For this case, fast egress and fixed CO_2 fire-extinguishing system basis fire fighting should be considered. Open spaces without bulkhead which shown in Fig. 9(b) is not considerable not only for lack of damage stability but also for fire safety because temperature among rooms and accesses rise concurrently and it disturbs egress and fire fighting activities. As shown in Fig. 9(c), the sliding shutter is helpful to gain time for egress and fire fighting compare to Fig. 9(a) and Fig. 9(b) even the sliding shutter is not entirely closed. Once the necessity of the sliding shutter has convinced through this simple and repetitive fire simulation, designer can consider detailed specifications of the sliding shutter in the next design process with field model basis computational fire simulation.

4.3. Contract basic design phase

Detailed equipment and facilities arrangement, furnishing plan, piping and instrument modeling for the layout selected during the preliminary basic design phase simulations allows for progression into the contract basic design phase. In this phase, specifications for fire fighting systems and the nozzle number and arrangement, should be determined for each POR. As the design freedom decreases, fire simulation-based design improvements become limited by the permitted budget and time. As the design becomes more concrete, field model-based fire simulations that require several simulations can be adopted. To form a fire safety plan, appropriate fire extinguisher specifications, number of nozzles and nozzle arrangements must be added to the design results and be evaluated. Fire fighting and evacuation procedures can then be applied to the fire safety plan.

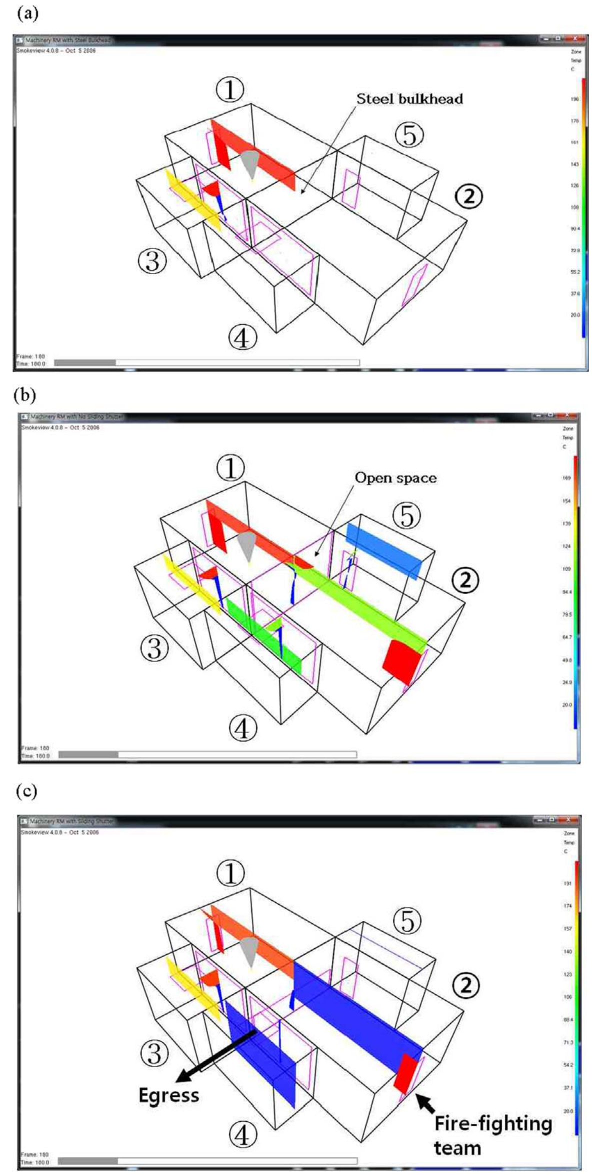


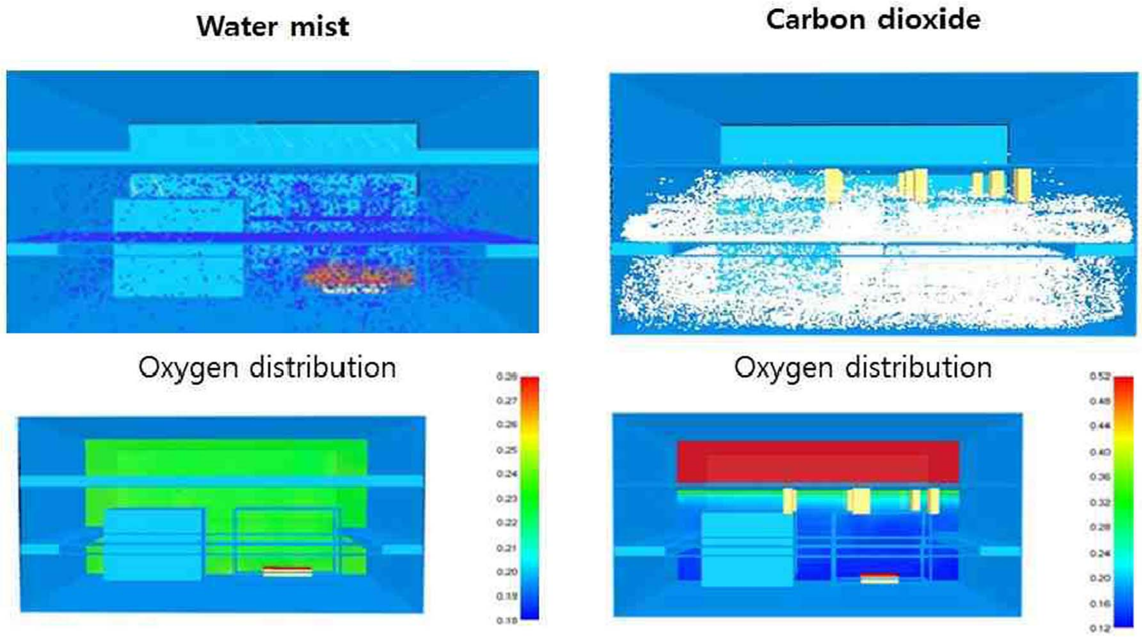
Fig. 9. Examples of zone model based fire simulation on machinery room with (a) steel bulkhead (b) open space (c) sliding-shutter.

Fig. 10 shows a field model-designed machinery room fire simulation. This simulation was used to evaluate the effect of water mist and CO_2 in the studied space. The nozzle arrangements, including the quantity, were then adjusted through repeated simulations. These simulations were used to determine a usable water mist and CO_2 mixture. Unlike CO_2, water mist can delay heat and smoke dispersion without lowering the oxygen level and temperature in the early fire fighting phases. Using water mist in a limited area can help field fire fighting workers perform their jobs longer than under conventional fire fighting conditions.

4.4. Further considerations

In this paper, the machinery room of the target ship has been utilized for the fire simulation. For the fire safety analysis of a ship, the ship locations, factors for the fire simulation, and simulation results shown in Table 3 are basically considered.

The ship design results should be evaluated and missing fire safety points have to be modified through a ship's life cycle. The fire safety plan reflects the ship design result. Though it is difficult to change the



Relative comparison of time for fire suppression

No. of Nozzle	6	9	12
CO_2	1	1	1
Water Mist	63.75	94.00	11.25

Fig. 10. Examples of field model based fire simulation in the machinery room.

Table 3
Zones, considerations and test target for the fire simulation of a ship.

Ship location	Factors for the fire simulation	Simulation result
Machinery room	Fire object	Heat (Dispersion time and level)
Living space	Door	Smoke (Dispersion time and level)
Cargo space	Windows	Sprinkler (Number and suppression time)
Galley	Detection	Water Mist (Number and suppression time)
Distribution	Initial reaction	CO2 (Number and suppression time)
Etc.	Fire suppression	Etc.

design result of a ship in operation, by gathering onboard fire fighting training results, the fire fighting drill and the fire safety plan of a ship can be enhanced through the ship's life cycle. Analyzed and stored onboard training data can be used for the fire safety design of a new ship. Therefore, it is possible to modify existing fire safety rules, regulations and guidelines without catastrophic marine accident occurrences. Fig. 11 shows implementation of a computational ship fire simulation framework throughout a ship's life cycle. From the suggested “Computational ship fire simulation framework”, hundreds of fire simulation data can be gathered in a fire safety assessment database after the contract design phase especially in the detail design. The fire simulation database is essential for developing the fire safety plan, which is specific to a ship design. In the face of a real fire accident in the operation phase, the database can support effective decision-making for damage control by showing estimated heat and smoke dispersion tendencies and behaviors. In the operational phase of a ship, the fire simulation database, along with the evacuation simulation and structural fire strength analysis database, can be used for stimulus modifying onboard fire fighting drill. Because fire simulation results can be linked to evacuation simulations and structural fire strength analyses during the design phase (Kang et al., 2012; Papanikolaou et al., 2009), decision-making support can be enhanced for the onboard crews in an emergency situation. For this reason, it is important to integrate the fire/smoke computation simulations applications with a modern OBTS (on-board incident management system and an on-board training system).

5. Conclusions

If budget and time permit, a full-scale fire test is the best way to ensure the fire safety of a newly constructed ship. However, every design process has limited budget and time. Therefore, computational fire simulations can be used during the ship design process. This paper presents a framework for using computational fire simulations during the early phases of ship design. Although there are numerous frameworks and fire safety schemes for ship design, applicable fire simulation frameworks should consider the increasing availability of data in each phase of the ship design process. The suggested computational fire simulation framework does not change the existing ship design process. In addition, the framework is organized within the bounds of internationally accepted frameworks, schemes and procedures. In the near future, we hope this study will help ship designers design ships with improved fire safety using existing methodologies, processes and tools.

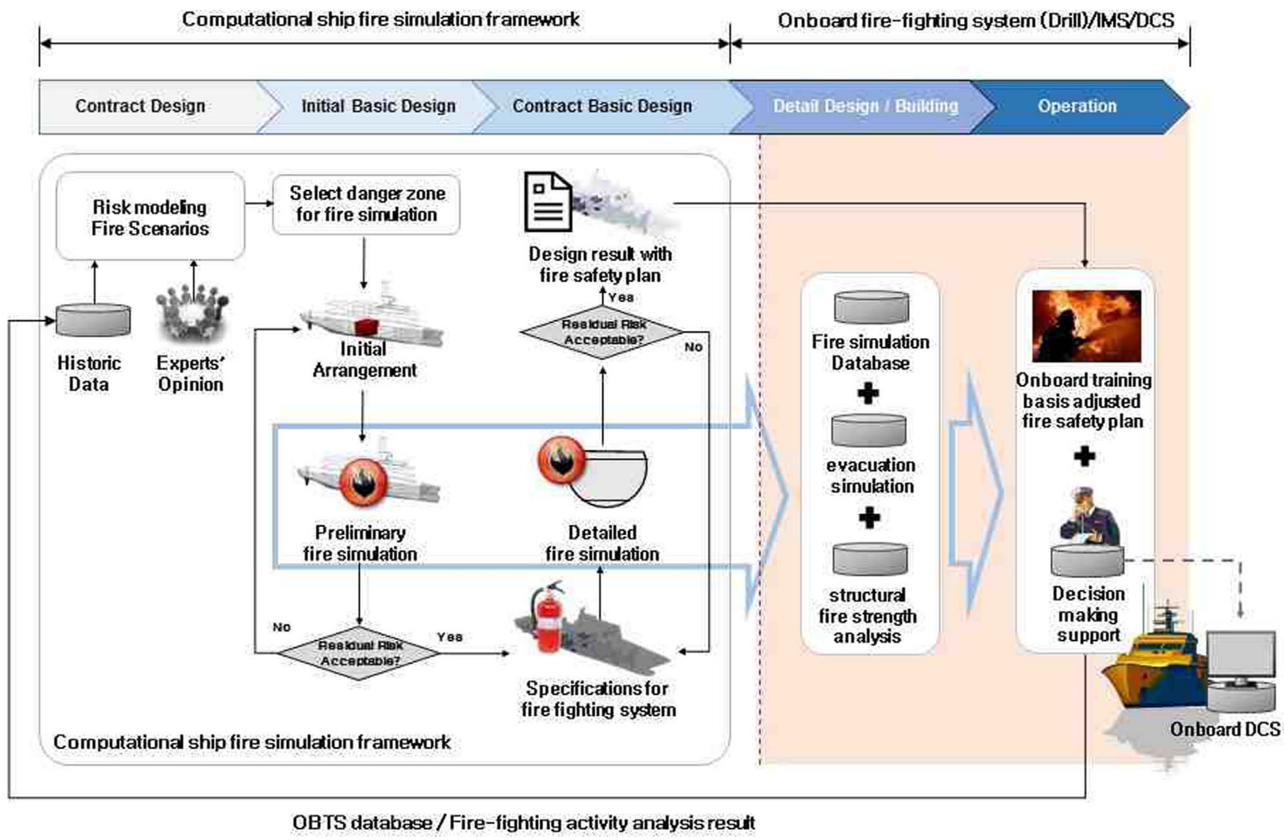


Fig. 11. Implementation of a computational ship fire simulation framework throughout a ship's life cycle.

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