Risk Assessment of Launching Airbags Using Functional Resonance Accident Model

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'Ship Launching Airbags' can greatly increase the economic benefits of a new gravitational launching operation. Gravitational launching of a new ship with marine airbags takes into account the resistance force of rolling friction. However, a launching operation is a high-risk process, as it involves many risk factors. In this paper, Functional Resonance Accident Model (FRAM) was used systematically to identify potential risks and carry out the risk analysis of the ship launching operation. The human factor, technical factors, and organisational factors were identified based on the common performance conditions of FRAM. Functional performance changes, prevention, and hazard control barriers were evaluated to identify key operations. The results show that the ship launching operation is characterized by high collision, decreasing stability, and the need for the use of airbags.

KEY WORDS

~ Functional Resonance Accident Model
~ Ship Launching Airbags
~ Risk Assessment
~ Risk Factors
~ Risk Control Barriers

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1. INTRODUCTION AND PROBLEM STATEMENT

Marine airbags are a new concept in ship launching systems. Rubber airbags lay out and inflate the airbags to lift the vessels and roll them into water. The airbag-rolling operation involves airbags, a vessel, and a towing system, and is characterized by collision and stability risks. Identifying key risk links in the launching process and proposing safety control measures to prevent accidents is imperative. The traditional risk analysis methods generally treat the factors of the potential accidents as an orderly occurrence of events (Evegren, 2017). However, the launching operation is a critical process in which multiple risk factors are closely coupled.

Marine airbags are robust and functional tools broadly utilized for ship launching, massive transportation at sea, and marine salvage. During a gravitational launch with marine airbags, the force of sliding friction transforms into the resistance force of rolling friction, which takes place during airbag rolling under the pulling and compressive forces related to the airbag bearing forces. Compared to traditional launching sledges, the rolling friction of marine airbags is much lower and needs a shorter launch slope. Airbags have a bigger contact area with the vessel bottom compared to launching sledges (blocks, trolleys), so the slipway is exposed to less pressure during launching. Calculation methodologies will enable the selection and optimization of airbag parameters, as well as the calculation of various stages of ship motion on airbags that will ultimately improve the effectiveness of airbag use.

Given the increasing use of gravitational launching with marine airbags, quantitative assessment of launching operations, including the safety of hull structure and airbags, is gaining importance. Therefore, risk analysis of launching operations has been carried out based on the motions and forces acting on a floating object. Quantitative calculations regarding hull structure and airbag safety, as well as the nonlinear rigidity of airbags, were ignored.

The reaction forces of airbags in terms of hull bending moment and local stress during the launching process may cause airbag explosion resulting in stability, grounding, and launching failures. The compressive forces of airbag bearing forces are highly nonlinear during the launching process. Therefore, getting some useful insights using the FRAM method for the risk assessment of airbag launching operations is imperative.

Some features of marine airbags are: launching process flexibility, straightforward operation, durable, recycled, and cost-effective. Marine airbags can be tailor made with respect to sizes and layers to meet the requirements of different launching projects. Due to simple operation, marine airbags can be used repeatedly allowing a significant reduction in launching or docking costs for shipyards or ship owners. Considering the flexibility of various launching projects, ship-launching airbags can be made in various sizes and layers depending on ship size and weight and launching or docking conditions in terms of effective length, diameter, and layers of airbags (CB/T 3837:1998). Their effective length should correspond to the ship's width or be 1 meter shorter for ships having the width of 5-24 meters, with various diameters available depending on the ship's size and work requirements. The more layers an airbag has, the greater its load bearing capacity. Lifting a ship requires a sufficient number of airbags with the sufficient number of layers. Usually, airbags with 6-8 layers are sufficient for most engineering works. However, in some cases, airbags need to withstand greater pressure and have more layers to ensure safety and enhance their performance (BS ISO 14409: 2011; BS ISO 17682: 2013).

Hollnagel (Hollnagel, 2007) first pioneered the FRAM and further reworked it in 2012 (Hollnagel, 2012). FRAM can be implemented by determining functions through the use of comprehensive information on how to achieve certain results, show function variability, view the likely interactions of the variability, and keep proposals and inferences to handle unpredictable variability. Recently, FRAM has been used in organisational change, offshore platform, and oil process unit assessment. Tian et al. (Tian et al., 2016) presented a FRAM-based realistic stage framework to reinforce risk analysis for socio-technical systems. The method was also used to examine a ferry accident. On the other hand, Patriarca et al. (Patriarca et al., 2017) strengthened the FRAM, offering a pioneering method based on Monte Carlo simulation, and presented a walkthrough section with applicable to an air traffic management process. FRAM treats accidents as sudden changes in regular system operation. From the viewpoint of the entire system, system function fluctuations that cause accidents and environmental factors that affect function fluctuations have been analyzed. Various launching operation risk factors are more fully and accurately identified, and safety measures for controlling risk factors proposed. FRAM has adopted a systematic and nonlinear qualitative approach to normal performance variability for system modeling. FRAM is also used to interpret safety target systems (Hirose et al., 2020), and identifies intended and unintended consequences of functional element dependency (Anvarifar et al., 2017). Additionally, from the proactive perspective, FRAM has been found to be a powerful hazard analysis mechanism which does not rely on linear cause-and-effect relationships (Leveson, 2012; Belmonte et al., 2011; Ishimatsu et al., 2014; Song, 2012; Bjerga et al., 2016; Rosa et al., 2015). FRAM analyses the combined causes of technological/technical, human or structural/organisational aspects. On the other hand, FRAM is also used to dynamically identify complex systems by their functions through modeling performance variability and non-linear dependencies (Patriarca et al., 2017; Patriarca et al., 2017; Hulme et al., 2019). Once the most important functions are identified, FRAM proposes improvements by defining the most proper mitigating activities to control risks and variability (Rosa et al., 2015). FRAM was first used in the maritime industry in 2011 (Salihoglu and Besikci, 2021; Praetorius et al., 2011, Praetorius et al., 2015, Smith, 2019, Patriarca et al., 2017). As for other accident case studies, FRAM provided an insight and improved our understanding of the potential origins of functional resonance in complex systems, also suggesting proactive countermeasures (Ferreira Pedro et al., 2019). Viran & Mentes (2022) used the FRAM method to model the basic functions of ship traffic management in the Turkish Straits region, which is one of the most critical examples of the narrow waterway concept, their mutual interactions, resonances, and risks.

Effective clues about system operation can be obtained by creating functional models of accidents occuring during ship launching. In complex interacting events, the FRAM method effectively explores potential system function variability. Therefore, the adoption of this method, capable of ensuring processes more reliable than traditional analysis processes, to ship launching systems for the first time will provide a rational perspective.

This paper is organized as follows: Section 2 contains specifications of marine airbags. Section 3 describes FRAM in terms of proactive perspective of launching, while Section 4 gives a description of ship launching using airbags. Section 5 provides the results of a launching operation. Finally, discussion and conclusion are given in Section 6.

2. MARINE AIRBAG SPECIFICATIONS

Airbags are classified by ordinary and high-bearing capacity corresponding to the bearing capacity. An airbag has a cylindrical structural body and two conical heads, one at each end. It consists of an outer rubber layer, synthetic-tire-cord layer(s), and an inner rubber layer. Prior to airbag production, airbag layers must be tested for any potential leakage and external load according to the rated working pressure to meet international criteria. All products must meet the test criteria for type approval, such as gastightness test, compression test, bearing capacity test, bursting test, and compression–recovery test. The ship must have a large flat bottom to come into proper contact with the airbags, ensure adequate bearing capacity and be suitable for rolling airbags. Furthermore, the bearing capacity of the slipway must be at least twice the working pressure of airbags to glide automatically in keeping with safety requirements (Yu et al., 2015).

The effective length of the airbag must not be shorter than the maximum width of the vessel. Arranging two rows of airbags is required to calculate the total length as an effective length plus diameter. Airbag diameter depends on the height of the vessel support block and should not be less than support block height. The performance of marine airbags depends on their component plies. While mid-pressure airbags are sufficient for airlift use or launch of light vessels below 2000 tons, heavy-duty work requires high-pressure airbags depending on the technological requirements for ships or optional specifications for a specific marine project (CB/T 3837:1998). Ship-launching airbags can be tailor made to customer's requests in various launching conditions, according to the bearing capacity of several sizes (BS ISO 14409: 2011; BS ISO 17682: 2013).

3. RISK ANALYSIS METHOD BASED ON FRAM

The basic principle of FRAM is the functional resonance theory evolved from the theory of stochastic resonance. Functional resonance is a sudden change in functional unit performance beyond the control range due to unintentional interaction of a number of other functional performance fluctuations (Patriarca et al., 2017). The performance fluctuations of the factors and the connection between these factors have been determined. Functional resonances and related factors have been identified. Safety evaluation methods for performance fluctuation management measures have been obtained (Tian et al., 2016).

In a complex system composed of multiple factors and subsystems, factors such as technology, personnel, and equipment are unstable and fluctuations are normal. For any given factor, other factors in the system can be considered its operating environment. The performance of a certain factor normally fluctuates (Leite et al., 2017). The performance fluctuation of the operating environment consists of the performance fluctuations of numerous factors which is indicative of an irregular state. If there is a correlation between the irregular fluctuation of the operating environment and the normal fluctuation of a factor's performance, it may cause system function resonance. The performance fluctuation of this factor will increase and spiral out of control, resulting in an accident (Salihoglu & Besikci, 2021).

3.1. Identification and description of system functions

Towing arrangements, retrieving airbags, and mooring systems undergo complex changes during vessel launching. Ship careening on the slipway, towing failures, and steel wire rope breaking are likely to occur, resulting in collision and accident. This not only causes huge economic losses but also threatens the marine environment. In this paper, the FRAM is used to explain how to induce accidents in the launching process. Human, technical, and organisational factors are identified based on common performance conditions of FRAM, after which functional resonances and related factors are obtained. Critical risk links of launching operations are qualitatively analyzed.

Step1: The function of the launching system is to set the vessel afloat. According to system function implementation process, the system can be divided into multiple functional modules. The function module is a function that is based on the entire system, rather than a simple structure or unit of the system.

Step2: Each function module has been explained using the hexagonal function chart and has six structural units, namely, I, O, C, P, T, and R. The detailed description of each structural unit is as follows:

Input (I) is the function that processes, transforms or sets off the function.

Output (O) are function results, i.e. either an entity or state change.

Control (C) is the manner of function observation or control.

Preconditions (P) are conditions that must be met prior to carrying out a function.

Time (T) is a temporal constraint affecting the function (starting time, finishing time or duration).

Resources (R) meet the function's execution conditions or are consumed to get the Output.

Step3: The connection between the various functional modules is established depending on their mutual relationships. Each functional module can be connected to multiple functional modules simultaneously, creating the FRAM functional network (see Figure 6).

Airbag and slipway specifications, and towing arrangements in facilities need to be determined. According to the implementation process of the system function, the system can be divided into multiple functional modules based on the entire system, rather than on a simple structure or unit of the system. Therefore, the connection between various functional modules is established depending on their mutual relationships, creating the FRAM functional network. As for the relationships between structural units and airbags, the center-to-center distance between two neighboring airbags depends on vessel weight and must comply with the regulations. Therefore, the location of the ship must be known to prepare the safety procedure to be applied when maximum airbag internal pressure and maximum internal pressure are reached. Launching is an operation accompanied by high slipway accident risk and a high-risk phase for both losses of stability and airbag accidents. Different variables of the relevant functions were used in the study, which also examined which influences on other functions resulted in loss of stability and airbag retrieval.

3.2. Identification and variability in function performance

FRAM determines a common performance condition that can affect system performance. In this method, the potential performance variability of the functional module needs to be evaluated to clarify how system function changes are affected by other parts of the system. Risk factors, i.e. various influencing factors of the launching operation have been identified and divided depending on its characteristics.

The performance variability of each functional module has been evaluated based on risk factors. Simple technological factors showed low variability, while social and psychological factors showed higher internal variability. The results of evaluation of common performance conditions can be *adequate*, *inadequate*, and *unpredictable*. Level ‘adequate’ shows that the probability of occurrence of the risk factor is low. The level ‘inadequate’ shows that the risk factor has a higher probability of occurrence. The level ‘unpredictable’ indicates that the probability of occurrence of the risk factor is very high. The performance variability status of each functional module is obtained by looking into performance condition evaluation results. Performance variability of functional modules is divided into four aspects: strategy, tactics, opportunity, and random. These four aspects represent fluctuations in functional performance, from small to large.

The performance of the ‘random’ functional module fluctuates greatly, making it susceptible to becoming a failure function module and generating functional resonance. Functional modules connected with the ‘random’ function module have been identified using the FRAM functional network. The influence of the failure of each relevant function module on the ‘random’ function module has been analyzed, and the influencing factors of functional resonance, and the connection of failure have been identified.

3.3. Development of prevention and control barriers

According to the analysis of the results of functional resonance options, the safety barriers for preventing collisions, compartment leakage, and airbag accidents have been proposed based on functional resonance risk factors and influencing factors. Safety barriers are the undesired events or accidents that should be prevented, mitigated, or controlled (Karolius et al., 2022). Safety barriers may range from a single technical unit or human action to a complex socio-technical system (Zhen et al., 2020). In the FRAM model, there are prevention and control barriers, namely physical, functional, symbolic, and invisible barriers, as follows:

1. Physical barriers: Barriers that prevent the occurrence of certain events and reduce the impact of emergencies.

2. Functional barriers: Barriers that establish one or more prerequisites to be fulfilled before acting.

3. Symbolic barriers: The obstruction function is played through the interpretative sign of restricted behavior.

4. Invisible barriers: The application scenario relies mainly on user knowledge to play a barrier role.

4. PROCEDURE OF SHIP LAUNCHING AIRBAGS

Some ship launching and facility specifications pertain to airbags, slipways, towing arrangements, launching procedures, and safeguards. The slipway requires a ship-specific launching cradle to be mounted on the hull above the slipway (a number of steel slipway runners, a large amount of wood, the application of grease onto the slipway runners, etc.) in the longitudinal sloping slipway. On the other hand, ship launching airbags eliminate these disadvantages by minimizing the cost of the launching cradle and environmental pollution.

There are four launching stages:

Stage 1: The perpendicular of the vessel enters the water once the movement begins.

Stage 2: The ship's aft end starts to float after 1st stage.

Stage 3: The ship passes onto the slipway threshold and is fully afloat after 2nd stage.

Stage 4: The ship comes to a full stop after 3rd stage.

The most dangerous stage is tipping on the slipway threshold. Pivoting pressures make the forward poppet of the ship subject to strong forces. Volenyuk and Rashkovskyi (Volenyuk et al., 2017) stated that float-off begins earlier and increases pivoting pressure.

A ship must have a flat bottom to ensure adequate bearing capacity for rolling airbags. The major equipment approved by the shipyard must be installed in position, all burrs and weld beads on the ship's bottom plates, as well as all appendages must be ground down. The shipowner must have completed water-tightness tests on all underwater compartments, and all the work on the shell plating. Furthermore, all mooring equipment and fittings are to be installed taking into account all loose items. The draft marks and load lines must be approved by inspection (BS ISO 14409: 2011).

4.1. Requirements for arrangements and equipment

The ramp, including its part protruding into water, is a slipway with a multitude of specifications. The launching area and slipways should be prepared to accommodate airbag facilities in terms of gradient, length, and bearing capacity. Defining airbag working pressure, vessel size, and the environment is paramount. The slipway must be made from reinforced concrete at least twice the working pressure of the airbags, which is determined depending on ship type, water level at the time of launching, and safety requirements. The difference in height between the right and left sides of the slipways must be less than 20 mm for ships over 3000 tons and less than 50 mm for ships below 3000 tons. The height difference between the right and left sides of the slipway for vessels heavier than 1000 tons must be less than 80 mm according to ISO requirements (BS ISO 14409: 2011; BS ISO 17682: 2013). On the other hand, airbags must meet technological requirements and standards (CB/T 3837:1998; BS ISO 14409: 2011). All airbags tested for any potential leakage must be filled to 1.25 times the rated working pressure without any external load applied before use. (see Table 3). In addition, the pressure must be maintained for at least one hour. The number of airbags required in any given launching operation is calculated using the following equation (BS ISO 17682: 2013):

$$N = K \times \frac{W \times g}{C_B \times R \times L_C} \qquad (1)$$

where '*N*' is the number of airbags, '*K* is the coefficient, *K* ≥ 1.2', '*W*' is ship weight (ton), '*g*' is gravity acceleration, *g* = 9.8 m/s2', '*CB*' is the block coefficient of the ship, '*R*' is the acceptable unit bearing capacity, kN/m, (see Table 3) and '*LC*' is ship and airbag contact length midship (m).

Two to four additional airbags must be made ready and available to move the vessel from the building berth to the vicinity of the water. Before launching, calculations must be made, including for additional airbags for vessels of above 5000 tons, for airbag placement, filling the airbags over the building blocks, removing the blocks, and letting the ship rest on airbags. The bearing load times the distance between the airbag and the ship's longitudinal center of gravity must be less than 1% of the ship launching weight times the distance between the perpendiculars. The center-to-center distance between two neighboring airbags must be less than or equal to and greater than that found in Equation (2) and Equation (3), respectively (BS ISO 17682: 2013). Airbag arrangement should provide the required ship stability and hull structure strength, taking into account center-to-center distance between two neighboring airbags.

$$\frac{L}{N-1} \leq 6k \qquad (2)$$

$$\frac{L}{N-1} \geq \frac{\pi \times D}{2} + 0.3 \qquad (3)$$

where, '*L*' is ship bottom contact length (m), '*k*' coefficient (*k* = 1 for steel ships, *k* = 0,8 for wooden, aluminum and glass-fiber-reinforced ships) and '*D*' nominal diameter (m)'.

In general, airbags must be arranged perpendicular to the direction of the motion (see Figures 1, 2 & 3).

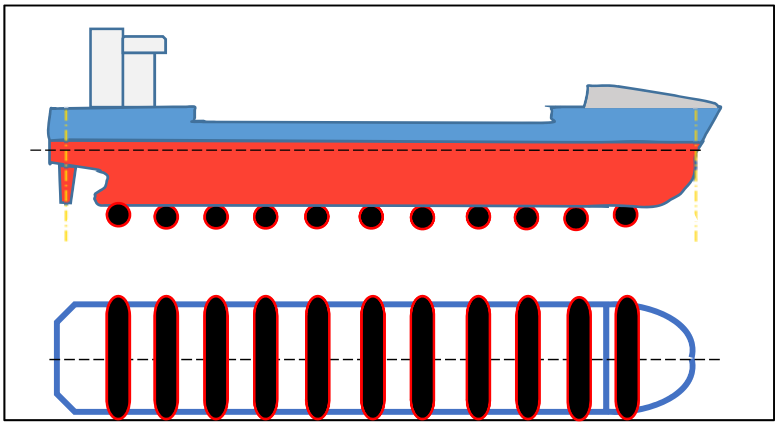

Figure 1. Linear arrangement.

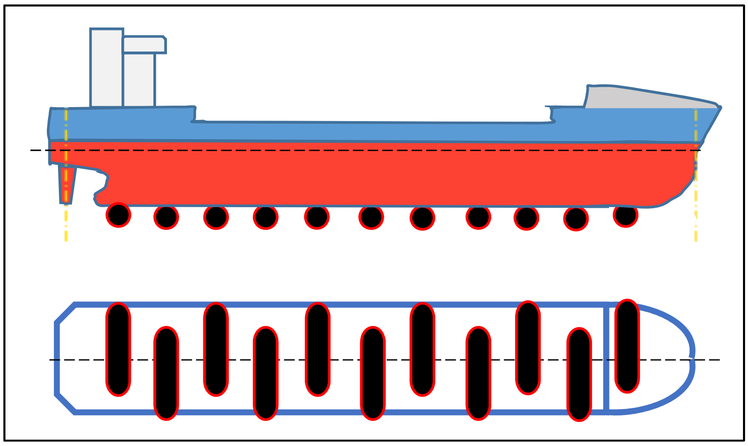

Figure 2. Staggered arrangement.

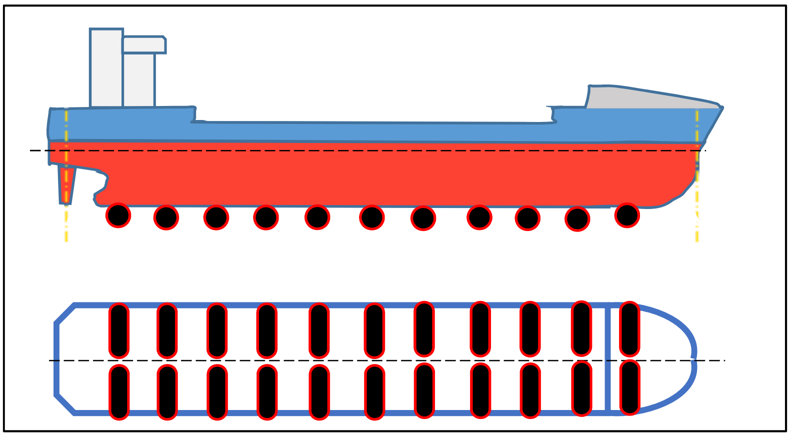

Figure 3. Two-line arrangement.

4.2. Towing arrangement

Ship movement is controlled by using towing system windlass, steel wire rope, and pulley. Fastening the ship to the ground anchor constructed in front of the berth is of great importance for mooring. Generally, the veering speed of the windlass must be 9-13 m/min for ship launching and the windlass must be securely fixed to the ground anchor (BS ISO 17682: 2013).

The design load of the ground anchor must be sufficient to withstand calculated pulling force (F). Steel wire ropes must meet ISO 2408 requirements with respect to the capacity of calculated maximum pull force (F) or calculated tensile force (Fc). The allowable pulley set, shackle, steel wire rope and rope clip loads must be sufficient for the calculated pulling force. Windlass must be checked and maintained regularly. Steel wire ropes must be inspected and changed regularly in keeping with the manufacturer's specifications. Forces acting on the towing system before the ship is set afloat are shown in Figure 4. Maximum tensile force must be calculated using Equation (4) and hauling force checked by Equation (5).

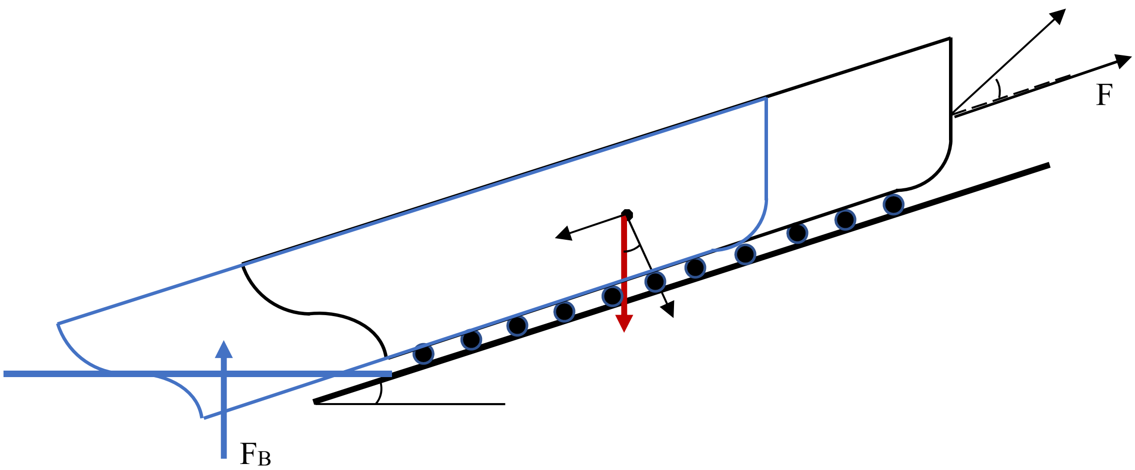

Figure 4. Force components of a ship.

$$F = W \times g \times sin\alpha - \mu \times W \times g \times cos\alpha + W \times \frac{V}{t} \quad (4)$$

$$F_C \geq \frac{K_1 \times F}{N_C \times cos\beta} \quad (5)$$

where,

'F' is maximum pulling force (kN) and 'F_c' is tensile force of the steel wire rope (N), 'α' is ground angle (degree), 'μ' is the friction coefficient of rolling airbags according to various factors in the regulation (BS ISO 17682: 2013), 'v' is vessel speed (m/s), 't' is the breaking time of the motion for the windlass (s), K_1 is coefficient (K_1 = 1.2 ~ 1.5), N_c is the number of steel wire ropes, β is the angle between the direction of maximum pull force (F) and the steel wire rope (degree). In general, it should not exceed 6°.

4.3. Ship launching procedure

The following documents must be prepared before ship launching:

a) General arrangement and lines plan,

b) Weight and center of gravity of the ship,

c) Lightship distribution curve, including ballast if any,

d) Hydrostatic curves or data and Bon-jean curves or data,

e) Main data about the berth and the launching slipway,

f) Docking block arrangement plan,

g) Report on the bearing forces on the slipway, and

h) Hydrological data such as water depth, tide table, and current speed.

Planning required before ship launching must include the following:

a) Ship's main dimension, weight and center of gravity, slipway and hydrological conditions,

b) Launching calculations, including specifications, quantities, bearing capacities, and airbag arrangements,

c) Hauling force calculations, hauling bat arrangements, windlass and steel wire rope arrangements, and

d) Planning ship transfer from docking blocks.

For ships above 5000 tons, calculations showing variations in the internal pressures of the airbags must be made for the entire ship launching operation. The location of the ship at the moment of maximum airbag internal pressure and attained maximum internal pressure must be made available for feasibility study and safety procedure preparation.

Additionally, operating procedure must be prepared before ship launching, including the following:

1) All obstacles on airbag route, including on the ship bottom, must be removed.

2) The bow of the ship must be tied to the windlass with mooring steel wire ropes. One end of the steel wire rope must be tied to the strength member of the ship, such as a bollard or a special horn, the other end to the pulley set of the towing system.

3) Airbags are placed under the ship as indicated in the plan.

4) Airbags need to be filled from stern to bow. Initially, airbags are not fully inflated. Once all airbags are inflated and in contact with the ship's bottom, they are filled to the specified pressure.

5) When airbags bear the weight of the ship, the docking blocks are removed. Airbag internal pressure should be adjusted to balance out forces after all docking blocks have been removed.

6) After workers and other personnel who stay on board during the launching board the ship, ladders and gangways are removed, etc.

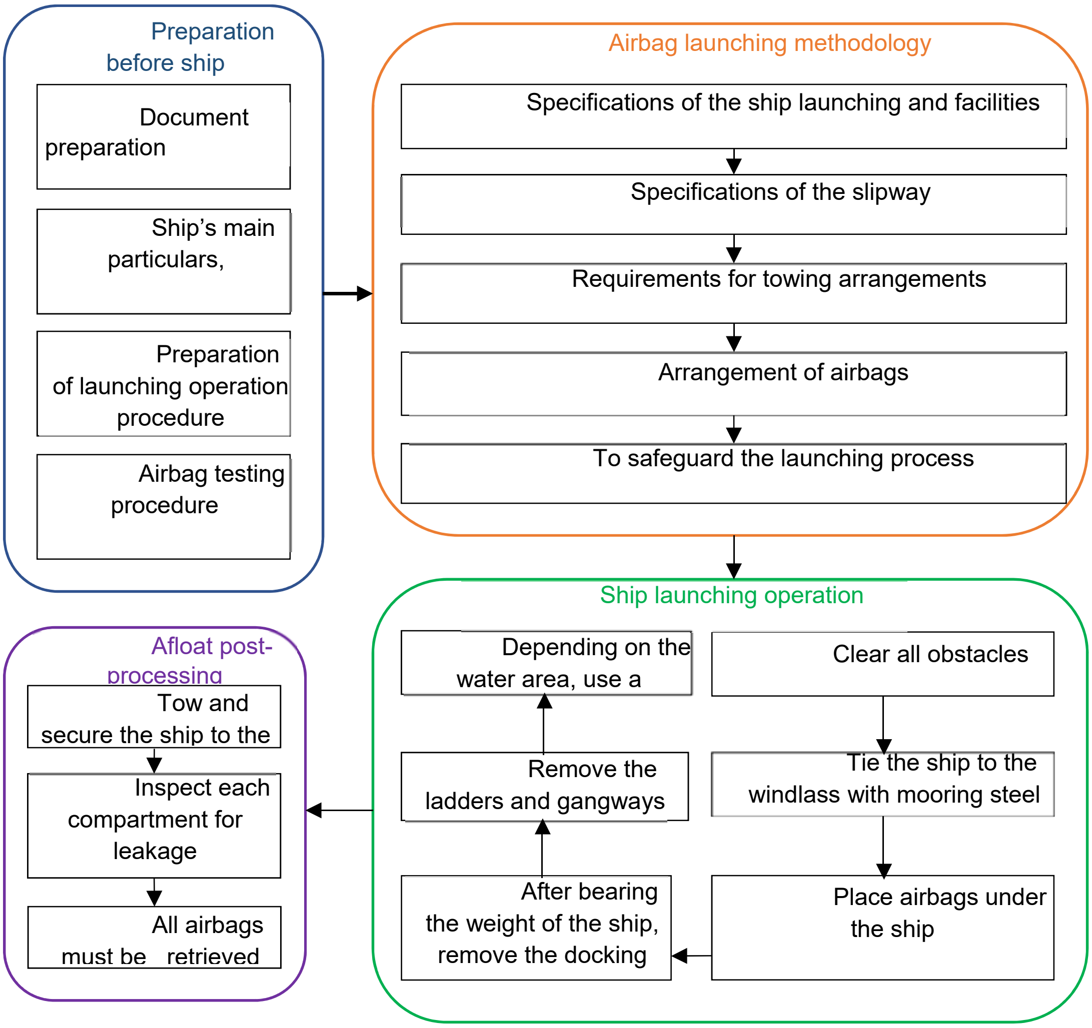

Figure 5. Ship launching operation flow.

7) Depending on the conditions of the slipway and area water, one of the following launching methods may be used:

a) If area water is wide enough, one can launch the ship by moving the ship to the water's edge, disengaging the windlass, removing or cutting the towline and letting the ship slide into the water by itself,

b) If water area is not wide enough, use the windlass to control launching speed and let the ship glide into the water slowly.

c) If the stern of the ship is built directly over the water and no windlass is available, the ship must be secured to the ground anchor by a rope before filling the airbags. Minimum water depth needed for launching must be calculated. The ship may be launched by cutting the rope or letting off the ground anchor when water is deep enough.

8) Once the ship is afloat, tow and secure the ship to the wharf, measure the bow and stern drafts, inspect each compartment for leakage.

9) All airbags must be retrieved.

10) All data for the launching operation must be recorded.

During the ship launching process, the launching team must determine ship characteristics, the geography of the launching site, and environmental conditions in great detail. They must also ensure that any emergency can be dealt with immediately. Each operator must have completed technical training and possess ship launching skills. Personnel filling airbags must stand on the side of the nozzle of each airbag. To avoid potential accidents, such as the steel wire rope coming apart or an airbag bursting, the danger zone must be identified and marked. The connection chart is shown in Figure 5.

5. RESULTS

5.1. Risk analysis of launching operations

Identification and description of launching system functions are as follows (Liu et al., 2022; Sugeng et al., 2020; Huilong et al., 2009).

Step1: Based on this system, the launching operation can be divided into fifteen functional modules, as shown in Table 1.

Step2: Each functional module is explained using the hexagonal function chart. Taking the function module ‘F9- Ship on slipway’ as an example, the detailed description is shown in Table 2.

Step3: Based on relationships between fifteen functional modules, the FRAM functional network of the ‘F9- Ship on Slipway’ launching operation has been established, as shown in Figure 6.

Table 1. Fifteen functional modules

F1-Determining the composition and duties of the personnel involved in ship launching operations **F2**- Communication conventions **F3**- Airbag performance testing **F4**- Inspection of ship launching equipment **F5**- Ship at the predetermined position **F6-** Steel wire cable connection between the ship and the windlass **F7**- Airbag retrieval **F8**- Ship mooring line connected to windlass, ground anchor	**F9**- Ship on the slipway **F10**-Tow and secure the ship to the wharf **F11**-Checking before towing **F12**-Initiate retrieval operation and other equipment **F13**-Finish the retrieval operation and other equipment **F14**-Inspect each compartment for leakage after retrieval **F15**-Vessel afloat

Table 2. Function module ‘F9- Ship on slipway’

Input (I)	-	Ship mooring line connected to windlass and ground anchor
Output (O)	-	Steel wire cable connection between ship and windlass

Resources (R)	- The launching team must prepare all details to safeguard the launching process, take into account ship characteristics, the geography of the launching site, and environmental conditions. - The entire towing system must be safely fastened to the ground anchor. - To avoid potential accidents, danger zone must be identified and marked.
Time (T)	-
Control (C)	- Towing system - Launching team - Speed of ship on the ground way - Launching procedures and precautions - Equipment responsible for communication between team members - Emergency plan
Precondition (P)	- Environmental conditions suitable for launching operations - Airbag testing for launching operations - Personnel involved in the launching operation and their duties are clearly defined

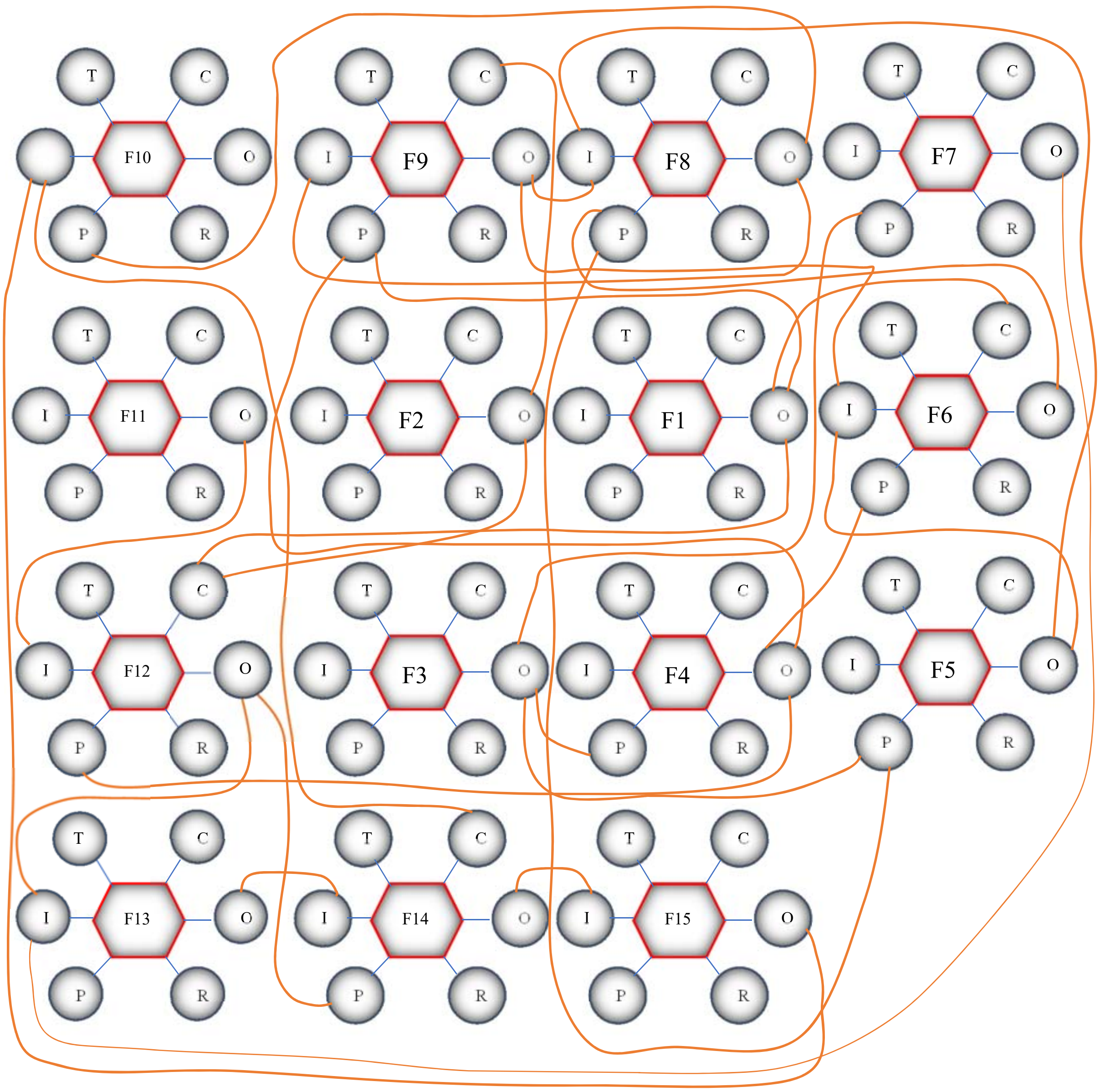

Figure 6. The FRAM network.

5.2. Assessment of potential performance variability for each functional module

During the launching procedure, depending on the implementation process of a system function, the system can be divided into multiple functional modules based on the entire system, not a simple structure or unit of the system. Therefore, the connection between various functional modules is established depending on the relationship between them, resulting in a FRAM functional network. According to the influencing factors of common performance conditions based on risk factors, the performance variability of the function in question can be evaluated based on the expert opinion of a group of academicians and ship launching field engineers.

Step1: The risk factors of the 'F9-Ship on Slipway' launching operation have been identified and divided based on the influencing factors of common performance conditions, as shown in Table 3.

Step2: Performance variability of each functional module has been evaluated based on risk factors. Function module 'F9- Ship on Slipway' was taken as an example and is shown in Table 3.

Step3: Performance variability evaluation results for the F9 functional module yielded 2 'adequate', 5 'inadequate' and 3 'unpredictable'. Performance variability of the F9 function can be evaluated as a 'random' state, indicating that the performance of the F9 function fluctuates greatly. Performance variability of the other fourteen functional modules can be evaluated in the same way. The distribution of three evaluation results across fifteen function modules is shown in Figure 7.

The performance variability state of the functional module can be evaluated as 'random' when the number of 'inadequate' ≥5 or 'unpredictable' ≥3; as 'opportunity' when the number of 'inadequate' ≥3 or 'unpredictable' ≥2; as 'tactic' when the number of 'inadequate' ≥2 or 'unpredictable' ≥1 and as 'strategy' when the number of 'inadequate' ≥1 or 'unpredictable' ≥0.

Therefore, the performance variability status of the F9 functional module is 'random', indicating that this function may generate functional resonances and become a failure function module.

Table 3. Common performance conditions of ship launching operation

Common performance conditions	Risk factors	Evaluation results
Quality and support of the organization	1) Failure of the major equipment approved by the shipyard. 2) Failure of all burrs and weld beads and all appendages inspected. 3) Failure of all the work required on the shell plating, and tests approved by the classification society in the compartments concerned. 4) Failure of all loose items, mooring equipment, fittings to be secured.	adequate
Conditions of work	1) The launching team must work out all details to safeguard the launching process by taking into account the ship's characteristics and environmental conditions. 2) To avoid potential accidents, such as steel wire rope snapping or airbag bursts, danger zone must be identified and marked.	Inadequate
Human-Machine Interface(HMI) and operational support	1) A towing system must be safely fastened to the ground anchor. 2) According to testing standards, type approval tests have not been carried out sufficiently.	Inadequate
Access to procedures and methods	1) The launching team did not strictly develop all details to safeguard the launching process.	Inadequate

	2) They did not ensure that any emergencies can be addressed immediately. 3) Every operator must complete technical training and have ship launching skills to avoid potential accidents 4) Danger zone must be identified and marked.	
Required time/available time relation	Once the ship is afloat, the time needed to tow and secure the ship to the wharf must be extended.	Unpredictable
Circadian rhythm and pressure	1) Poor psychological tolerance of operators 2) Operator fatigue and work panic 3) Depression	Unpredictable
Training and experience	1) Operators do not have clearly defined responsibilities and do not have ship launching skills. 2) A new operator controls the main operation link without any supervision.	Adequate
Crew collaboration/ communication quality	1) This is the first time that the launching team has worked together. 2) The division of work management responsibilities is confusing. 3) Communication system failure	Inadequate Unpredictable
Availability of resources	1) Testing procedure failures. 2) The towing line between the ship and the windlass disconnected. 3) Steel wire cable old, mooring equipment missing or damaged. 4) Failure of airbag connection equipment and fittings. 5) Not all airbags have been retrieved.	Inadequate

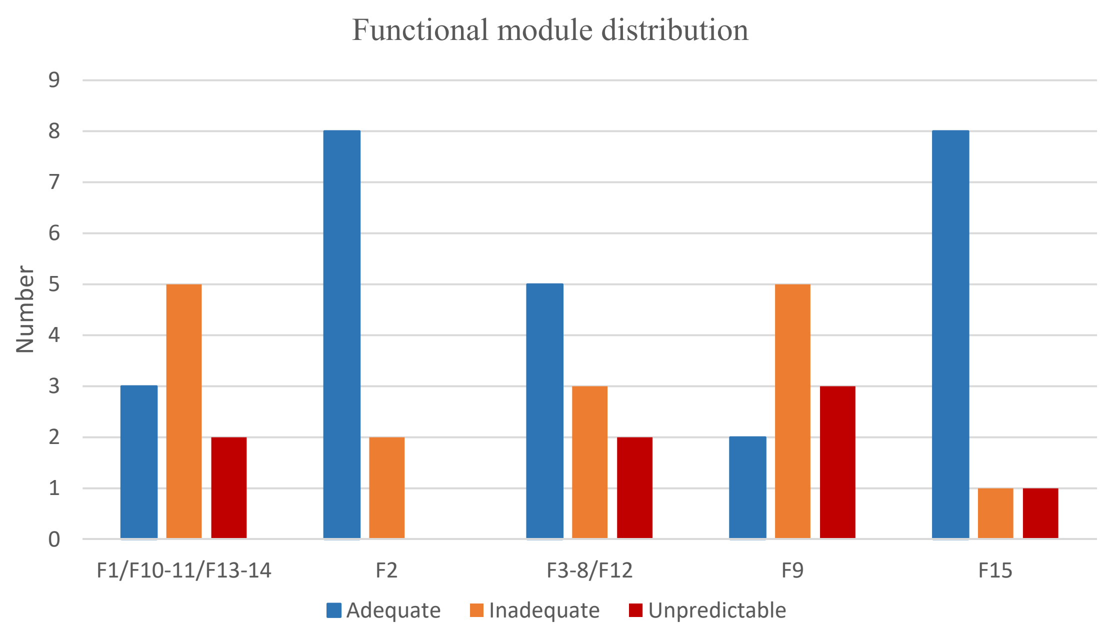

Figure 7. The distribution of three evaluation results across fifteen function modules.

5.3. Identification of possibilities for functional resonance

Performance variability of the F9 function module has been evaluated as ‘random’. Therefore, this functional module has been analyzed to identify the functional resonance module, influencing factors, and failed connections. During the execution of the F9 function, due to the low speed of the ship, the forces of the towing system have a greater impact on the ship. If the launching team fails to adjust the berthing operations of the vessel to airbag state changes on time, the likelihood of collision accidents and loss of stability increases. Therefore, the launching team is the core part of launching operations. If the steel wire rope between the vessel and the windlass is disconnected, it may cause a sudden increase in the ship's speed and loss of stability on the slipway. During the launching operation, it is necessary to communicate in real-time and finally determine the docking position. If cooperation is inadequate, there is risk of accidents on slipways, steel wire cable snapping, or airbag loss. The results of functional resonance analysis for the F9 functional module are presented in the following table.

Table 4. Functional resonance and failure connection of the F9 functional module.

Functional resonance unit	Functional resonance influence factors	Failed function connection
F1- Determining composition and duties of the personnel involved in the ship launching operation	**F9**（C） - Launching team overall quality	**F9**（O） **- F6**（I）
F8- Ship mooring line connected to windlass, ground anchor	**F9**（C） - Ship speed on the slipway	**F9**（O） **- F8**（I） **F9**（O） **- F6**（I）
F2- Communication conventions	**F9**（R） - In-team communication	**F8**（O） **- F10**（P）

5.4. Development of prevention and control barriers

According to the analysis results of functional resonance options, the risk control measures for preventing collisions and leakage accidents have been proposed based on the risk factors and functional resonance influencing factors, as shown in Table 5.

Risk control measures for ship launching operations include barrier type explanations, namely physical and functional barriers. Physical barriers reduce the impact of emergencies, while functional barriers require prerequisites to be fulfilled before performing an action.

On the other hand, the obstruction function of symbolic barriers involves interpretation of restricted behavior, while invisible barriers mainly rely on user knowledge to prevent accidents. These risk control measures, depending on obstacle type, are the philosophy behind the ship's launching operations.

Table 5. Risk control measures of ship launching operations.

Obstacle type	Performance fluctuation control measures
Physical barriers	1) Always have the launching team in the area during launching operations. 2) Estimate all details to safeguard the launching process, taking into account the ship's characteristics, the geography of the launching site, and environmental conditions. 3) Adjust the slipway forces to the forces acting on the steel wire cable connection in a timely manner, to prevent the cable from pulling too much and breaking. 4) All loose items, all mooring equipment, and all fittings have to be secured. To avoid potential accidents, such as the steel wire rope snapping or airbag bursts, the danger zone must be identified and marked.

	5) Shorten operator emergency response time through early warning of parameters such as vessel speed and location on the slipway, and internal airbag pressure. Improve emergency recovery capabilities and avoid accident escalation. 6) Before initiating the launching operation, determine weather and sea conditions in the area and avoid conducting launching operations in extreme weather.
Functional barriers	1) Before a launching operation, operational, emergency training, and ability assessments should be made to ensure that all team members are qualified for their jobs. 2) The team manager determines the condition of the slipway, water area, and airbags. 3) In the course of the launching operation, the launching team must work out all details to safeguard the launching process and ensure that any emergency can be dealt with immediately. 4) Regular equipment maintenance, airbag testing procedure, timely replacement of damaged parts, and drawing up inspection records.
Symbolic barriers	1) Towing arrangements should be equipped with steel wire ropes capable of withstanding calculated pulling forces. 2) Providing visual images of the vessel on the slipway to increase awareness of the position of the vessel in real-time so that airbag and stability risks can be identified on time.
Invisible barrier	1) Draw up a management plan and define reasonable specifications for the ship's launching and facilities. 2) Simulation training should focus more on the launching operation and emergency response capabilities. 3) Every operator participating in the ship launching procedure must have completed technical training and ship launching skills to ensure that any emergency can be dealt with immediately. To avoid potential accidents, danger zone must be identified and marked.

Risk control measures for preventing collisions, leakage accidents, and loss of stability were identified based on functional resonance influencing factors and risk factors based on the analysis of functional resonance in the launching application. Therefore, ship launching barriers must be explained by using the FRAM model more intuitively and systematically.

6. DISCUSSION AND CONCLUSION

Launching airbags are utilized for cost-effective ship launching, haulouts, loading, and floating. They are flexible, portable, and dependable, save labor and time. Marine Airbags overcome some disadvantages of traditional sliding launching. As inflated rubber airbags have certain elasticity, the ship can tilt slightly during launching without suffering any damage. There is sufficient contact between the ship hull and the airbags to minimize hull stress. Flexible and versatile rubber airbags allow the launching of vessels of different types, sizes and weights. Launching can be executed in simple and tough-conditioned banks or beaches. Flat ground can be used as a dock way. Airbag launching needs a simple inclined dock way with flat ground, airbags, an air compressor, some wire, and a winch.

Once the ship is afloat, to avoid potential accidents such as the steel wire rope snapping or an airbag bursting, tow and secure the ship to the wharf, inspect each compartment for leakage and retrieve all airbags. Accident triggering was analyzed by using the FRAM model during the ship launching procedure, taking into consideration facility specifications based on relationships between technical details. On the other hand, the launching procedure was conducted and specifications of facilities such as airbags, slipway, and towing arrangements determined by using the FRAM model more intuitively and systematically. The assessment of the potential performance variability of each functional module based on the influencing factors of common performance conditions, is actually a qualitative analysis used to obtain the expert opinions of a group of academicians and ship launching field engineers. The main goal was to understand how launching airbags work by developing functional models of launching failures. Specific prevention and control measures for preventing loss of stability and retrieving airbags have been proposed.

In this study, the FRAM model was used to explain which conditions trigger accidents. Human, technical and organisational factors were identified based on common performance conditions. According to these factors, launching operation functional modules on slipways were evaluated. The performances of ‘Launching Operation’ and ‘Start retrieving operation and other equipment’ fluctuate greatly. The results of functional resonance analysis show that ‘Launching operation’ is key to high accident occurrence on the slipway. ‘Start retrieving operation and other equipment’ is also a high-risk stage where both loss of stability and airbag accidents may occur. FRAM avoids unilaterally causal sequence analysis and single-factor analysis of the launching accident process. It explains the evolution of multiple risk factors present during launching more intuitively and systematically.

The operation of launching airbags was explained by developing functional models of launching failures. The FRAM method identified the potential functional variability of obtaining much more reliable processes. When FRAM was applied to launching airbags, critical functions that cause loss of stability on slipways were identified. Then, different variables were used in these functions together with influencing functions. Specific prevention and control measures for preventing loss of stability and ensuring airbag retrieval can be proposed.

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