ORIGINAL RESEARCH (AR) DOI: 10.4274/jems.2023.79847

Journal of ETA Maritime Science 2023;11(4):222-231

Quantitative Failure Analysis of the Ballast Pump System Onboard a Ship under HAZOP and the Extended CREAM Approach

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Abstract

Improper ballasting can lead to severe damage, potentially resulting in loss of life, vessel damage, and environmental disasters. This paper systematically assesses system failures in ballast pump operation related to human errors that contribute to operational risks. Considering this objective, we developed a hybrid approach that combines the Cognitive Reliability and Error Analysis Method (CREAM) with Hazard and Operability (HAZOP). Within this study's context, HAZOP analysis is harnessed to pinpoint the risks inherent in intricate ballast operations, a crucial component of maritime safety. By integrating CREAM analysis, a comprehensive understanding of the role of human factors in systematic failures and operational risks is achieved. The research emphasizes the critical role of cognitive activities, including monitoring, planning, diagnosing, and maintaining, in ensuring the safe and efficient operation of ballast pump systems. This study highlights the importance of cognitive functions such as observation, planning, interpretation, and execution in addressing these issues. The HAZOP analysis successfully identifies various potential deviations and failures within the system, providing insights into the complex nature of ballast operations and the significance of human factors. The analysis method effectively pinpoints vulnerabilities and weaknesses, underlining the necessity of meticulous planning and proper execution to mitigate identified failures. By not only delineating the fundamental causal factors behind ballast system failures and the potential consequences of these failures but also aiming to elevate safety control measures, this paper strives to mitigate prospective losses in critical shipboard operations.

Keywords: Maritime safety, HAZOP, CREAM, Ballast pump system, Safety operation

1. Introduction

Operational safety vulnerabilities often stem from stability issues, posing substantial risks tied to inadequate ballasting, excessive partial loading, heightened environmental forces, and suboptimal planning [1]. Recent years have witnessed significant maritime accidents that have resulted in substantial environmental damage, primarily due to instability during ballast water exchange. The ill-conceived ballast water exchange on the MV Cougar Ace caused its capsizing, narrowly escaping vessel loss in 2006 [2]. Within minutes, the vessel rolled more than 60 degrees due to the starboard ballast tank's failure to refill [3]. Likewise, MV Capri's blackout in 2017 resulted from incorrectly set ballast system valves and unexecuted de-ballasting procedures, triggered by a hammer effect caused by water pressure [4]. Ballast operations are integral to a ship's stability, ensuring that stress values (e.g., bending moments, shear forces, slamming) and other factors such as draft, trim, and propeller immersion remain within acceptable limits [5]. Ballast water is indispensable for safe and effective ship operations because it enhances manoeuvrability counterbalances weight loss due to fuel consumption and compensates for buoyancy changes. Given the precision and speed required, ballast operations demand utmost accuracy and compliance with relevant authorities such as the IMO, Class, and Port State. The complexity of these operations varies with vessel capabilities and ballast systems, transpiring within a dynamic working environment [1], necessitating immediate detection and response to forestall system-wide failures that could lead to hull damage,

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Received: 25.08.2023
Last Revision Received: 12.09.2023
Accepted: 18.09.2023

To cite this article: M. Aydın. "Quantitative Failure Analysis of the Ballast Pump System Onboard a Ship under HAZOP and the Extended CREAM Approach." *Journal of ETA Maritime Science*, vol. 11(4), pp. 222-231, 2023.

listing, or capsizing [6]. Responsibility falls significantly on the master and chief officer as decision makers and supervisors. They are tasked with planning, executing procedures, and maintaining records for ballast operations in compliance with set requirements. Crew members also require awareness of instructions and control procedures. Consequently, human performance assessment has emerged as a critical parameter for identifying potential hazards in vital shipboard activities [7].

Risk assessment and hazard identification hold paramount importance for shipowners, safety inspectors, engineers, and practitioners, given the inherently high-risk nature of most shipboard operations [8,9]. While some studies have presented applicable methods for maritime risk assessment [10-12], research specifically focusing on human error-based risks in ballast operations remains limited. Existing ballast water risk assessments mostly target harmful marine species that endanger human health, the economy, or the environment [13-15]. Considering the comprehensive literature review, various studies have explored the correlation between human error and ship ballast system failures [16-20]. However, despite this existing body of research, there remains a scarcity of in-depth investigations specifically addressing the intricate interplay of human factors in ballast pump failures. Recognizing this research gap, this study proposes a quantitative root cause analysis for ballast pump system failures. It does so by employing the Cognitive Reliability and Error Analysis Method (CREAM) integrated under the Hazard and Operability (HAZOP) framework to assess potential risks.

To achieve this, the paper is organized as follows: the importance of the study and the gravity of ballast failures are addressed in this section. Given the significance of each method, the subsequent section elucidates their theoretical foundations and their integration within the proposed approach. Section 3 showcases the meticulous application of this approach to shipboard ballast operations, while Section 4 encapsulates the research findings, conclusions, and contribution to maritime transportation.

2. Methodology

A hybrid approach is introduced to incorporate CREAM under HAZOP techniques to evaluate operational root causes and quantitative analysis of ballast operations onboard ships. In this study, HAZOP conducts systematic analysis of the ballast pump system and identifies deviations from the intended functioning and their causes and implications. At this point, the CREAM techniques that provide quantitative results are incorporated with HAZOP to prioritize the actions to mitigate identified failures. CREAM quantifies human error probability (HEP).

2.1. HAZOP Analysis

HAZOP is the most prominent hazard identification technique that provides a structured and comprehensive review of a defined system to identify the causes and consequences of deviations from the design intent [21,22]. It can identify potential hazards and operational problems not only for plant design but also for human error [23]. The HAZOP produces qualitative results that depend on the use of guide words that inquire how the intentions or operating conditions of system design might are not met at any point (Fuentes-Bargues et al. [24]), as illustrated in Table 1. HAZOP is usually performed during a series of meetings by a multidisciplinary team. In the meetings, the system, process, or procedure to be assessed and the specifications of the intention and performance are defined. The guidelines are then applied to check operating conditions and detect design errors or potentially abnormal operating conditions for each of the variables that influence the process [24].

Table 1. *Guide words for HAZOP*

Guide words	Interpretations	Examples
No	Failure to complete the task	The operator skips the next step
Less	Performing less than required	Completing a reduced amount due to partial valve openings
More	Performing more than required	Opening valves excessively, leading to a larger amount of processed
Reverse	Doing the opposite of the intended action	Closing valves instead of opening them
Part of	Incomplete execution of necessary actions	Omitting certain actions within a step
As well as	Additional actions in conjunction with the main task	Processing extra material by opening an additional valve
Other than	Actions deviating from the intended task	Processing of wrong material due to valve error
Sooner	Executing the action ahead of schedule	Rapid action by rearranging the step sequence
Later	Execute the action after the specified time	Delayed action by altering the step order
Other	Accounting for the various factors influencing the action	Considering shift changes as a contributing factor

The responsible teams must choose the parameters specific to each analysed system. Table 2 (Crawley et al. [25]) provides instances of potential parameters applicable to process operations.

2.2. CREAM

CREAM, a second-generation HRA method, was initially introduced by Hollnagel [26] to analyse cognitive human errors and reliability within nuclear power plant contexts [27]. Modified CREAM has been employed to quantify human error and assess human reliability in specific maritime applications [28,29]. It offers both retrospective and prospective analyses (Akyuz and Celik [9]) for diagnosing and predicting error-related events. In the prospective analysis, the basic and extended versions of CREAM evaluate human reliability. The basic version screens human errors (Rashed [30]), determining control modes and corresponding error rate intervals. The extended method quantifies cognitive function errors by building upon the outcomes of the basic version [26]. Both deterministic approaches must handle uncertainties in a common performance configuration (CPC). Prospective analysis identifies human errors, whereas retrospective analysis quantifies them [31], thus enhancing overall system safety through error identification and quantification. The CREAM model was chosen because it aligns with the objectives and context of our study for evaluating human errors. This model extensively delves into human cognitive processes and decision-making mechanisms, making it suitable for examining human errors within complex systems. Furthermore, the CREAM model provides a probability-based assessment of human errors, enabling quantitative analysis of potential risks.

2.3. Integration of Methods

The integration process encompasses two primary phases. The first phase involves the application of HAZOP, which consists of two key sub-stages: "Determining Process Parameters and Deviations" and "Identifying Possible Causes and Consequences." This method critically evaluates the process parameters and deviations, systematically exploring potential causes and consequences within the analysis. Moving forward, the second phase encompasses the CREAM approach, which unfolds across four distinct sub-stages: "Assessing Common Performance Conditions (CPCs)," "Identifying Context Influence Index (CII)," "Determining Performance Influence Index (PII)," and "Calculating Cognitive Failure Probability (CFP)." Within this method, a comprehensive evaluation takes place, appraising CPCs and gauging the influence of contextual factors. PII and CII indices contribute to delineating the potential impact of cognitive failures. The final step, CFP calculation, quantifies the probability of cognitive errors occurring. This integrated methodology combines the strengths of HAZOP and CREAM, fostering a holistic analysis that encompasses process parameters, deviations, possible causes, and consequences, along with cognitive factors.

Table 2. *Examples of parameters used in process operations*

Pressure	pH	Operate	Monitoring
Flow	Reaction	Phase	Signal
Mixing	Composition	Speed	Start/stop
Stirring	Temperature	Transfer	Aging
Particle size	Addition	Measure	Maintain
Level	Sequence	Control	Diagnostics
Time	Separation	Viscosity	Services

2.3.1. Determining the process parameter and deviation

In this phase, the paramount goal is to define process activities for shipboard operation, attuned to the prevailing context. Employing hierarchical task analysis (HTA), the main task is divided into subtasks Shepherd [32], forming a basis for HEP quantification. This systematic approach enables tailored error prediction calculations to assess associated risks. For HAZOP implementation, the initial steps involve identifying system parameters, evaluating them within the system's context, and selecting context-specific guide words. Subsequently, the focus shifts to potential parameter deviations as vital indicators of hazards. HAZOP guides researchers by suggesting precautionary measures linked to identified deviations, thereby enhancing risk management strategies.

2.3.2. Identifying possible causes

The following deviation identification, the team delves into uncovering potential causes and their subsequent outcomes. Each deviation's underlying causes are methodically examined, ensuring individualized evaluation. Thorough consideration of all potential causes is essential before finalizing the assessment process. Notably, deviations with substantial or critical consequences require immediate investigation. This phase ensures a comprehensive exploration of the origins of deviations, enhancing the understanding of their potential effects.

2.3.3. Assess common performance conditions (CPCs)

The CPC implies performance shaping factors that influence the value of HEP and determine the context of human perception and behaviour. Nine CPCs were introduced by CREAM to define several error modes and causes. Table 3 shows the degree of CPC and its corresponding performance implications and performance influence index (PII) values [33].

***Table 3.** CPC level, performance effect, and PII values*

CPC	CPC level/description	Effects	PII
Adequacy of the organization	Very efficient	Improved	-0.6
	Efficient	Not significant	0
	Inefficient	Reduced	0.6
	Deficient	Reduced	1.0
Working conditions	Advantageous	Improved	-0.6
	Compatible	Not significant	0
	Incompatible	Reduced	1.0
Adequacy of MMI and operational support	Supportive	Improved	-1.2
	Adequate	Not significant	-0.4
	Tolerable	Not significant	0
	Inappropriate	Reduced	1.4
Availability of procedures/ plans	Appropriate	Improved	-1.2
	Acceptable	Not significant	0
	Inappropriate	Reduced	1.4
Number of simultaneous goals	Fewer than capacity	Not significant	0
	Matching the current capacity	Not significant	0
	More than capacity	Reduced	1.2
Available time	Adequate	Improved	-1.4
	Temporarily inadequate	Not significant	1.0
	Continuously inadequate	Reduced	2.4
Time of day	Daytime (adjusted)	Not significant	0
	Night-time (unadjusted)	Reduced	0.6
Adequacy of training and experience	Adequate and high experience	Improved	-1.4
	Adequate, limited experience	Not significant	0
	Inadequate	Reduced	1.8
Crew collaboration quality	Very efficient	Improved	-1.4
	Efficient	Not significant	0
	Inefficient	Not significant	0.4
	Deficient	Reduced	1.4

To determine the probability of human error by considering the effect conditions, the CPC scores are computed. After the final CPC scores were obtained, the control modes were established to assess the HEP interval. The combined $\sum reduced$ and $\sum improved$ scores have the required control mode that practically guarantees the probability of a human failure interval. Meanwhile, the important CPC does not affect the value of the HEP such that it is not considered. In the meantime, the HEP value is not influenced by CPC $\sum not\ significant$, so it is not considered.

2.3.4 Identify the Context Influence Index (CII)

To simplify calculation, CII is used for quantifying CREAM, in particular CPCs. This value can be measured by subtracting the number of CPCs decreased from the improved CPCs displayed in Equation (1), where X represents the number of decreased CPCs and Y corresponds to the number of improved CPCs [27].

$$CII = X - Y = \sum reduced - \sum improved \qquad (1)$$

2.3.5. Determine the Performance Influence Index (PII)

This stage generates PII values to determine correct weighting factors for entire cognitive functions, such as observation, planning, interpretation, and execution. As seen in Table 1, each CPC has a different PII value; therefore, different weigh factors play a role. It is a matter of obtaining precise quantitative results of the CSPs by using the PII values, instead of the linguistic expression (improved, decreased or not significant). This computation can only be used during the screening process, but never in detailed quantification [27]. In view of this, Equation (2) becomes feasible for the CII value.

$$CII = \sum_{i=1}^{9} PII \qquad (2)$$

The PII value in the equation depends fundamentally on the weighting factor provided in the extended CREAM method and evaluated by experts [27]. Therefore, the value of the cognitive failure probability (CFP) can be obtained by weighting and classifying the CPC in critical applications.

2.3.6. Calculation of Cognitive Failure Probability (CFP)

The CFP refers to the expectation of human failure for each form of cognitive failure to measure the HEP value. The CFP value (HEP) will be determined after the nominal cognitive failure probability (CFP_0) for each subtask has been assigned. CFP_0, which is obtained mostly from different sources, refers to the numerical value for cognitive function failure [26]. The CFP, which was mainly gathered from various sources, denotes the nominal value provided for failures of cognitive function [26]. The CFP table with respect to the four cognitive functions is given in Table 4 [26].

In this respect, it is possible to establish the association between CII and CFP using equation (3). The logarithmic function in the equation is used to explain changes in the relationships between humans and the variation in external conditions. The underlying assumption is technically acceptable [34].

$$\log\left[\frac{CFP}{CFP_0}\right] = k.CII \qquad (3)$$

where k is the coefficient of constant and is derived from Equations (4) and (5), respectively [21].

***Table 4.** Nominal cognitive failure probability and the lower upper bond*

Cognitive function	Generic failure type	Lower bond (0.5)	Basic value	Upper bond (0.95)
Observation	O1. Wrong object observed	3.0E-4	1.0E-3	3.0E-3
	O2. Wrong identification	2.0E-2	7.0E-2	1.7E-2
	O3. Observation not made	2.0E-2	7.0E-2	1.7E-2
Interpretation	I1. Faulty diagnosis	9.0E-2	2.0E-1	6.0E-1
	I2. Decision error	1.0E-3	1.0E-2	1.0E-1
	I3. Delayed interpretation	1.0E-3	1.0E-2	1.0E-1
Planning	P1. Priority error	1.0E-3	1.0E-2	1.0E-1
	P2. Inadequate plan	1.0E-3	1.0E-2	1.0E-1
Execution	E1. Action of the wrong type	1.0E-3	3.0E-3	9.0E-3
	E2. Action at the wrong time	1.0E-3	3.0E-3	9.0E-3
	E3. Action on the wrong object	5.0E-5	5.0E-4	5.0E-3
	E4. Action out of sequence	1.0E-3	3.0E-3	9.0E-3
	E5. Missed action	2.5E-2	3.0E-2	4.0E-2

$$\log(CFP_{max}/CFP_0) = k.CII_{max},$$

$$\log(CFP_{min}/CFP_0) = k.CII_{min} \tag{4}$$

$$k = \log(CFP_{max}/CFP_{min})/(CII_{max} - CII_{min}) \tag{5}$$

$$\mathrm{CFP}_0 = CFP_{max}/10k.CII_{max} \tag{6}$$

According to the specific control modes and CII values, the maximum CII value can be 9 and the minimum CII value can be 7. In the equation the $\mathrm{CFP}_{\mathrm{max.}}$ is accepted as 1.0000 (maximum HEP value), which indicates certainty for the probability of human error. The $\mathrm{CFP}_{\mathrm{min}}$ is accepted as 0.00005 (minimum HEP value), which indicates almost impossibility. Then, *k* is found to be about 0.26. As a result, in the case of a definite CII value, the following equation (7) can be adopted to determine the adjusted CFP (HEP value) [35].

$$\mathrm{CFP} = \mathrm{CFP}_0 \, \mathrm{x} \, 10^{0.26.\mathrm{CII}} \tag{7}$$

4. Quantitative Failure Analysis for Ballast Pump System on Board Ships

In maritime operations, the ballast pump system significantly influences vessel stability and manoeuvrability. This analysis enhances operational safety by systematically evaluating failures and establishing mitigation measures for the ballast pump system on ships. These measures are essential for crew, vessel, and environmental safety. This section outlines the procedures for conducting quantitative risk analysis of the ballast pump system. The assessment includes hazard identification and evaluation of failure likelihood and potential control actions. Hazard identification involves scrutinizing potential issues that could affect the ballast pump system. The following identification, assessing the likelihood of human error failures quantitatively gages risks. Strategies to reduce these risks, such as design modifications and personnel training, are then evaluated for effectiveness. By quantitatively analysing risks within the ballast pump system, maritime operators can proactively enhance vessel safety and reduce environmental impact.

4.1. Problem Statement

While ballast pump systems are integral to maritime operations, ensuring vessel stability and safe maneuverability, the complex interplay of factors exposes these systems to potential risks. Despite their significance, a comprehensive quantitative analysis of these risks, encompassing hazard identification, likelihood assessment, and formulation of effective risk reduction strategies, remains limited. Consequently, the maritime industry lacks a structured approach to systematically quantify and address potential vulnerabilities within ballast pump systems. This study aims to bridge this gap by developing a rigorous quantitative failure analysis framework for ballast pump systems on board ships, contributing to enhanced operational safety, crew protection, and environmental conservation. Operational errors during ballast pump usage underscore the importance of this study. Improper valve configurations can lead to water distribution imbalances, resulting in vessel instability and listing. Neglecting water flow rate monitoring might lead to tanks being overfilled or underfilled, thereby affecting the vessel's trim, stability, and overall performance. Disregarding operational protocols may delay response time during emergencies due to incorrect sequencing of actions. Insufficient crew training can hinder effective ballast pump system operation, compromising decision making during critical situations. In addition, neglecting routine maintenance and inspection increases the likelihood of equipment malfunctions, potentially jeopardizing crew and vessel safety. These examples highlight the multifaceted nature of errors that can occur during ballast pump operations.

4.2. Numerical HAZOP Analysis

To assess system failures in ballast pump operation related to human errors that contribute to operational risks in ballast pumps, a detailed HAZOP framework is required. The HAZOP team was selected to determine the relevant process parameters and potential deviations (failures). The team consists of nine marine experts who have wide knowledge and experience of shipboard operations. HAZOP parameters and guide words have been presented to marine experts, and a brief introduction has been performed for detailed HAZOP risk analysis. Most of the experts are deck superintendents and master mariners. The experts have also been asked to advise potential causes of deviations in case of ballast pump system operational failures. Because of the parameters and deviations determined by the consensus of marine experts, the potential causes of deviations have been identified. Potential causes were considered separately for each deviation. To address potential causes, shipboard ballast operation is assessed in depth. Deviations might have more than one possible cause. Accordingly, a detailed HAZOP Table 5 is created. To quantify HAZOP deviations, which give potential failure of the system, a systematic extended CREAM is used. The PII values have been nominated in the view of marine expert consensus. Table 6 shows the PII values of CPC for each deviation in the system. To gather the cognitive failure probability (CFP) of deviation (failure) in the system, four cognitive functions are used: observation, interpretation, planning, and execution. Equation (7) is used to calculate the adjusted CFP for each deviation in the ballast pump system. Table 3 shows the cognitive function and basic failure rates. Accordingly, Table 7 shows the results of adjusted CFP values along with relevant cognitive activity, cognitive function, and generic failure type.

4.3 Findings and Extended Discussion

The HAZOP analysis, as demonstrated in Table 5, identified several potential deviations or failures within the system. These deviations (failures) encompass scenarios where water does not reach the pump, the pump suction level is near the waterline, ship trim affects pump suction, water cannot be delivered to the tank, the pump operates inadequately, the pump's capacity is low, there is a slow increase or decrease in tank levels because of unintentional ballast operations, and the liquid level in a tank increases unexpectedly. For each of these deviations, cognitive activities such as monitoring, planning, diagnosing, and maintaining were noted. The corresponding cognitive functions involved observation, planning, interpretation, and execution. The HAZOP analysis method successfully highlighted potential issues across various operational stages. The deviations identified provide insights into where failures might occur, and which cognitive activities and functions are involved in addressing these issues. It is evident that careful planning and proper execution are crucial for mitigating the identified failures. For instance, deviations related to pump performance underscore the importance of maintaining and diagnosing equipment to ensure reliable operation. Similarly, addressing deviations due to unintentional ballast operations requires effective planning and execution strategies.

The CREAM analysis method yields quantitative results through cognitive failure probability (CFP) values calculated for each potential deviation. These values enable a comparative assessment of their potential impact and range across deviations, with adjusted values reflecting the seriousness of the associated failure mode. This structured approach facilitates the assessment and prioritization of potential failures based on their estimated impact. By assigning CFP values, the CREAM analysis offers a quantitative perspective on potential system failures, enabling effective allocation of resources for mitigation strategies. This aid decision-making by highlighting failures with the greatest potential consequences and streamlining the focus on areas of concern.

Among the deviations highlighted in Table 7, deviations (failures) 4, 6, and 8 stand out due to their notably high adjusted CFP values, indicating significant potential risks within the system. In the Table 7, no 6, "Low-capacity working," boasts adjusted CFP of 1.82E-01. Requiring monitoring and observation, the high adjusted CFP value accentuates the substantial impact that low-capacity working can have on the overall system performance. Addressing this issue promptly through corrective actions, such as performing maintenance to enhance pump capacity or replacing malfunctioning components, is crucial to prevent potential repercussions.

Similarly, no 8, the "Liquid level increasing in tank" deviation, holds adjusted CFP of 1.27E-01. Centred on monitoring and observation, the elevated adjusted CFP value underscores the notable risk linked to unexpected liquid level increases within a tank. Swift interventions, such as installing additional level sensors or implementing automated alert systems, are imperative to effectively manage this situation and mitigate potential adverse effects.

Lastly, no 4, involving the deviation "Water not delivering tank," has an adjusted CF of 8.65E-02. This deviation, which necessitates diagnosis and interpretation, underscores the substantial risk associated with improper water delivery to the tank. To avert any adverse consequences, measures to ensure accurate water delivery, such as regular inspections of valves and pipelines or the implementation of redundant delivery systems, should be of utmost priority.

Table 5. *HAZOP table for the ballast pump system on board ship*

No	Process (target)	Keyword	Guide word	Potential deviations	Potential cause	Outcome	Existing control actions	Additional control actions
1	Line up and set up/ correct valve position	No	Water	Water not reaching the pump	1) Wrong line up/valve operation	No ballast water intake	1) Check line up again 2) Check the pump suction and pressure gages 3) Check overboard visibly (deballasting)/ check tank level change (ballasting)	1) Ensure that the ballast pipeline diagram is prepared correctly 2) Ensure manual operated valves are marked with the correct code
					2) Sea chest/filter blocked			
					a) Fouled by sea creatures		Clean up by back flushing/steaming	Proper cleaning during the dry dock period
					b) Fouled by garbage		Clean the sea chest filter	Avoid ballast operation in shallow waters/ low draft when sea chest is close to the surface at garbage fouled ports
				Pump suction level close to the water line			1) Use a pump priming unit 2) Use the existing ballast tank as line filling for initial suction	1) Install the pump on the lower platforms. 2) Proper draft calculation before ballast operations
				Ship trim and/or list not suitable for pump suction from ballast tank.	1) The wrong cargo/ballast sequence 2) An improper stowage plan 3) Improper dich/load port sequence	Node ballasting	Internal ballast transfer for sufficient trim/list Internal cargo transfer (if possible)	Proper stowage plan Proper planning of the cargo ballast disch. sequence Proper cargo dish/load port sequence
2		Yes	Pressure	Water not delivered to tank	1) Manual valve not operating 2) False indication of the remote valve indicator light (vise versa) 3) Remote valve actuator does not open/close (due to rust on valve spindle), but indicator shows that the valve is operating 4) Remote valve actuator hydraulic leakage	No ballasting	1) Overhaul the valve 2) Test with gravity ballasting/de-ballasting on a regular basis and prior port arrivals 3) Visual inspection and valve overhaul 4) Check the hydraulic storage tank level regularly 4.2) Ensure that the hydraulic tank low-level alarm is working	Start operation with gravity ballasting to prevent pressure surge on the pipeline

Table 5. *Continued*

2	Run the pump and generate the pressure	No	Pressure	Pump not properly running	1) Power source switch turned off 2) Loose wire/wire broken 3) Electric motor failed 4) Pump impeller fouled with nylon string	No ballast/ reballast	1) Check engine room for the main power source is on 2) perform the Megger test. Replace wire 3) perform the Megger test. Rewind the electric motor 4) Overhaul the pump	Use a second pump or any other general service pump if connection is available
		Low	Performance	Low capacity working	1) Unused valve left open pump circulate 2) Impeller worn out (clearance gap is big)/ impeller 3) The pump case has a crack/hole. 4) Pump gland leakage	Low ballasting performance	1) Check line up 2) Overhaul the pump and change the impeller 3) Temporary clogging of the hole with fast drying agents. 4) Change the pump gland packing	Performance test of the pump regularly Regular visual inspection of the pump Check the suction and pressure gage of the pump
3	Run the pump and fill in the intendent tanks	No/ low	Level	Level increase/ decrease slow Unintentional ballast operation	1) Line ruptured in transit of another tank 2) Valve seat worn out 3) Check valve disk is lost 4) Pipeline connection failure	Low ballasting performance	1) Clog the hole with temporary clamping	1) Replace line at dry dock time 2) Conduct regular line pressure test 3) Check for non-operational tank level change
4	No ballast operation	Yes	Level	Liquid level increasing in the tank	1) Hull damaged 2) Sounding pipe cover left open 3) Ballast manhole cover unsecured properly/gasket failure 4) Air vent head floating disk not operational 5) cargo tank/hold has cracks in ballast tanks	Unintended list due to water/cargo penetration	1) Temporary clog hull with wood chocks 2) Pre-departure check prior departure 3) Pre-departure check prior departure 4) Replace the floating disk 5) Plan to deviate from safe ports	1) regular thickness measurement 2) Keep the temporary hull clogging equipment agents' tools on board

Table 6. *PII values for deviation*

	PII value							
CPC	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Adequacy of the organization	0.6	1	0	1	0.6	0.6	0.6	0
Working conditions	0	1	0	1	0	1	0	1
Adequacy of the MMI and operational support	0	-0.4	-0.4	0	0	-0.4	-0.4	-0.4
Availability of procedures/plans	-1.2	0	0	-1.2	-1.2	1.4	1.4	1.4
Number of simultaneous goals	0	0	-0.4	0	0	-0.4	0	0
Available time	1	1	1	-1.4	1	-1.4	1	-1.4
Time of day	0	0	0.6	0,6	0	-0.6	0	0
Adequacy of training and preparation	-1.4	-1.4	0	0	-1.4	0	-1.4	1.8
Crew collaboration quality	0.4	-1.4	0.4	-1.4	0	1.4	0	-1.4
Total	**-0.6**	**-0.2**	**1.2**	**-1.4**	**-1**	**1.6**	**1.2**	**1**

Table 7. *Adjusted CFP values along with relevant cognitive activity, cognitive function, and generic failure type*

No	Potential deviation/failure	Cognitive activity	Cognitive function	Generic failure type	Nominal CFP (CFP0)	Adjusted CFP
1	Water not reaching the pump	Monitor	Observation	O3	7.0E-02	4.89E-02
2	Pump suction level close to the water line	Monitor	Observation	O1	1.0E-03	8.87E-04
3	Ship trim and/or list not suitable for pump suction from ballast tank	Plan	Planning	P2	1.0E-02	2.05E-02
4	Water not delivered to tank	Diagnose	Interpretation	I1	2.0E-01	8.65E-02
5	Pump not properly running	Maintain	Execution	E4	3.0E-03	1.65E-03
6	Low capacity is working	Monitor	Observation	O3	7.0E-02	1.82E-01
7	Level increase/decrease slow unintentional ballast operation	Maintain	Planning	P2	1.0E-02	2.05E-02
8	Liquid level increasing in the tank	Monitor	Observation	O3	7.0E-02	1.27E-01

Given the distinct potential risks associated with high adjusted CFP values, these deviations necessitate immediate attention and proactive mitigation strategies. By focusing on these areas of concern, the system's overall reliability and operational safety can be effectively preserved. The quantitative perspective provided by the CREAM analysis aids in informed decision-making by highlighting failures with the most substantial potential impacts and guiding the allocation of resources for focused mitigation efforts.

5. Conclusion

This study focused on addressing potential failures associated with ballast pump systems in maritime operations. By employing the CREAM integrated within the HAZOP framework, this study has offered valuable insights into the complex nature of ballast operations and the significance of human factors in these processes.

The HAZOP analysis effectively identified various potential deviations and failures within the system. The findings underscore the critical role of cognitive activities, such as monitoring, planning, diagnosing, and maintaining, in ensuring the safe and efficient functioning of ballast pump systems. The cognitive functions of observation, planning, interpretation, and execution correspondingly play a pivotal role in addressing these issues. The analysis method has successfully highlighted potential concerns throughout different operational stages, demonstrating the effectiveness of the method in pinpointing vulnerabilities and weaknesses.

CREAM analysis provides a quantitative perspective on the potential impact of failures within the system. By assigning CFP values, it is possible to prioritize areas of concern based on their adjusted values. This aids decision-making processes by highlighting which failures might have the most significant consequences, helping allocate resources for mitigation strategies more effectively. To guide potential researchers in this area, it is recommended that future studies include a section that outlines specific methodological improvements. This section discusses how the HAZOP and CREAM analyses can be further enhanced or refined to yield more accurate results. Suggestions for incorporating real-time data into the analysis and exploring a wider range of variables should be emphasized. Despite the insightful findings and contributions, this study has certain limitations. The analysis relies heavily on historical data and assumptions, which might not fully encompass all scenarios. The focus on cognitive aspects might overlook other technical, mechanical, or environmental factors that contribute to failures. Future studies could expand the analysis to encompass a wider range of variables, integrate real-time data for a more accurate assessment, and explore comprehensive training programs for crew members to enhance their cognitive performance during ballast operations.

In summary, this study sheds light on the significance of human performance and cognitive aspects in mitigating potential hazards in shipboard ballast operations. By integrating HAZOP and CREAM methodologies, this study provides a systematic approach for identifying, analysing and addressing potential failures, thus contributing to the enhancement of maritime operational safety and efficiency.

Peer-review: Externally and internally peer-reviewed.

Funding: The author received no financial support for the research, authorship, and/or publication of this article.

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