

RISK ASSESSMENT OF FUEL OIL BUNKERING OPERATIONS USING AN INTEGRATED HIRARC–HAZOP FRAMEWORK: A CASE STUDY AT A MARINE JETTY TERMINAL

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Abstract

Integrated Terminal Makassar's fuel oil bunkering operations at Jetty 1 and Jetty 2 present significant, intertwined occupational and process hazards. This study analyzed these risks by integrating Hazard Identification, Risk Assessment, and Risk Control (HIRARC) with Hazard and Operability (HAZOP) studies, a novel approach for conventional fuel bunkering. HIRARC identified nine hazards across preparation, transfer, and completion stages, initially rated as low risk, subsequently reduced to low or very low via predominantly administrative controls. HAZOP analysis revealed deeper process deviations underlying these occupational hazards, including communication failures, excessive pressure and flow rates, hose integrity degradation, slippery deck conditions, and inadequate residual fuel handling during completion. The integrated HIRARC-HAZOP framework demonstrates that occupational risks directly correlate with process deviations, a connection often overlooked by single-method analyses. While existing controls are functional, three critical areas require reinforcement: formalizing pre-transfer communication checklists, establishing hose integrity documentation beyond visual inspection, and procedurally mandating the draining and disconnection sequence at operational completion. These refinements aim to enhance safety by moving beyond reliance on spontaneous compliance towards a robust, procedurally driven safety management system.

Keywords: Bunkering Safety, HIRARC, HAZOP, Integrated Risk Assessment, Occupational Hazards, Process Deviations

INTRODUCTION

Integrated Terminal Makassar serves as a primary fuel distribution node in eastern Indonesia, managing loading, unloading, and bunkering operations at Jetty 1 and Jetty 2 for vessels requiring fuel for generators and main propulsion engines. Fuel transfer at a marine jetty is inherently high-exposure: flammable cargo, pressurized equipment, and direct human involvement converge in a confined space where a single deviation can escalate rapidly. Fuentes-Bargues et al. (2017) documented this hazard complexity in fuel terminal operations, yet their analysis addressed onshore configurations and does not resolve whether these findings extend to the vessel-terminal dynamics of marine bunkering.

Bunkering is a sequence of operationally linked stages, each carrying its own risk profile, where hazards most often accumulate at the transitions between stages rather than within them. Khan et al. (2025) applied Bayesian network modeling to bunkering risk, identifying spills, equipment failure, and human error as dominant drivers, though their probabilistic framework was not designed to examine what occurs at the occupational activity level, where workers sustain direct physical exposure to flammable environments throughout. Fan (2024) approached the problem through human reliability analysis in LNG bunkering, a methodologically significant contribution that nonetheless does not translate to conventional fuel oil transfer, where manual-operational conditions and worker-equipment proximity differ substantially from cryogenic handling contexts. Neither study examined the interaction between occupational hazard and process deviation within a conventional petroleum bunkering setting, and it is precisely that interaction that determines whether a risk framework is practically usable or analytically complete only on paper. A structured literature search was conducted in Scopus covering 2020 to 2025, using three keyword combinations: bunkering risk assessment, HIRARC occupational safety, and HAZOP fuel terminal. From nine deduplicated records, no study satisfied the inclusion criteria of peer-reviewed research on bunkering operations, jetty transfer safety, or integrated occupational-process risk analysis in conventional fuel contexts; retrieved results

were concentrated in LNG, ammonia, and hydrogen bunkering, where regulatory urgency has directed research attention (Fan, 2024; Khan et al., 2025). The narrowness of this retrieval reflects deliberate search specificity: broader individual-method searches return larger result sets, but those results address HIRARC and HAZOP in isolation and do not speak to the integration gap this study targets. HIRARC has been applied extensively in manufacturing and construction (Junaidi et al., 2020; Wong et al., 2022), while HAZOP has been applied to fixed-plant oil and gas systems (Pérez-Marín & Rodríguez-Toral, 2013); neither has been integrated within a conventional fuel bunkering framework. That absence is not a neutral observation. It is the empirical basis on which this study's contribution rests.

The novelty of this study lies not in HIRARC or HAZOP individually, both of which are well-established, but in their deliberate integration as a unified analytical framework applied specifically to conventional fuel oil bunkering at a marine jetty terminal. Ardiansyah et al. (2026) demonstrated the feasibility of this integration in non-bunkering industrial settings, a precedent that does not account for the vessel-terminal interface, tidal variability, and dual maritime-industrial jurisdictions characteristic of bunkering. Accordingly, this study aims to analyze risks in bunkering operations at Jetty 1 and Jetty 2 of Integrated Terminal Makassar through an integrated HIRARC–HAZOP approach, with objectives of systematic occupational hazard identification, process deviation analysis at critical transfer nodes, and evidence-based risk control recommendations.

THEORETICAL FRAMEWORK

The primary risk categories in bunkering operations have been documented across multiple independent studies, though with meaningful differences in emphasis. Iannaccone et al. (2018) established the foundational hazard profile through incident analysis in marine fuel handling, identifying leaks, equipment failure, and fire potential as dominant categories. Khan et al. (2025) confirmed that this structural landscape has not changed substantially despite advances in transfer equipment. Ceylan (2025) approached the same territory from an occupational angle, centering human fatigue and exposure as persistent contributors that equipment-level analysis routinely underweights. Their findings converge on a conclusion none states explicitly: bunkering risk is distributed across human behavior and process mechanics in a way that resists capture within any single analytical framework.

Occupational safety risks in bunkering arise from direct worker involvement across all operational stages, each carrying distinct exposures to fuel contact, surface hazards, communication failure, and physical fatigue. Ceylan (2025) identified these exposures as structurally recurrent across bunkering contexts, though without comparative analysis of control measure performance across varying terminal configurations, limiting the study's generalizability. Fan (2024) examined the problem through human reliability analysis in LNG bunkering, producing methodologically significant findings on operator cognition under pressure, though these are bounded by the cryogenic and automated conditions of LNG handling, which diverge substantially from the manual-operational environment of conventional fuel oil transfer. Reading occupational risk through probabilistic models alone is insufficient where the quality of human-environment interaction is the primary risk driver.

HIRARC is a structured risk assessment approach that traces work activities to hazards, evaluates likelihood and consequence severity, and prescribes controls within a hierarchy prioritizing engineering controls above administrative measures and personal protective equipment (Saedi et al., 2014; Zaman et al., 2023). Its orientation is fundamentally fieldwork-centered, designed to read risk from what workers actually do rather than what process diagrams indicate should happen (Junaidi et al., 2020; Wong et al., 2022). Junaidi et al. (2020) and Fathullah et al. (2023) demonstrated this strength in manufacturing contexts, where HIRARC surfaced hazards that more abstract process-oriented methods had not captured. Its principal limitation is a boundary in scope rather than a flaw in design (Ardiansyah et al., 2026; Hutauruk et al., 2026): HIRARC can identify and score a hose mishandling event, but cannot systematically trace whether that mishandling propagates into pressure anomaly, valve failure, or process-level emergency.

HAZOP examines process systems through guide words applied to parameters at defined nodes, identifying deviations and tracing their causes, consequences, and safeguard adequacy (Chen & Jia, 2015; Johnson, 2026). Pérez-Marín & Rodríguez-Toral (2013) demonstrated its capacity to surface deviation scenarios in oil and gas systems that conventional inspection would not detect, while Fuentes-Bargues et al. (2017) confirmed this effectiveness in fuel terminal environments specifically. Jeong et al. (2025) further established its compatibility with marine multi-system operational contexts. Its limitation, however, is symmetrical to HIRARC's gap (Jain et al., 2018): HAZOP can identify that valve malfunction leads to overpressure, but is not structured to ask why an operator failed to detect early warning signs, or how communication breakdown contributed to delayed response. In bunkering, where behavioral dimensions are often the initiating condition for process deviation, that peripherality is a substantive gap.

The limitation of each method, read against the other, constructs the argument for integration. Stefana & Paltrinieri (2020) demonstrated that no single method sufficiently captures the full risk profile of complex sociotechnical systems, and that integration consistently produces more actionable findings (Naeini & Nadeau, 2022). In bunkering, where occupational hazard and process deviation are structurally porous to each other, HIRARC–HAZOP integration addresses both analytical layers simultaneously, a move that non-bunkering literature has begun to explore but not yet extended to conventional fuel terminal contexts (Ardiansyah et al., 2026; Jung et al., 2025).

Within this integrated framework, risk control elements occupy distinct but complementary positions across both methods. SOPs, checklists, and training function as administrative controls in HIRARC's hierarchy, targeting worker behavior and procedural compliance (Saedi et al., 2014; Susanto et al., 2024; Zaman et al., 2023), while simultaneously serving as safeguard layers in HAZOP's node analysis, where their presence or absence determines whether a deviation is contained or escalates (Fuentes-Bargues et al., 2017; Johnson, 2026). Spill response equipment operates by the same logic: a last-resort control in HIRARC and a consequence-mitigating safeguard in HAZOP (Fuentes-Bargues et al., 2017; Khan et al., 2025). Recognizing this dual function has direct implications for how control recommendations are formulated and prioritized. The method through which this integrated framework was operationalized at Jetty 1 and Jetty 2 is described in the following section.

METHOD

This study employs a descriptive approach with semi-quantitative risk analysis through an integrated HIRARC–HAZOP framework. A semi-quantitative approach was selected over fully quantitative methods because historical incident data and detailed operational records at Integrated Terminal Makassar were not available in sufficient completeness to support probabilistic frequency estimation. Under these conditions, semi-quantitative analysis offers a methodologically defensible middle ground: it preserves structured scoring and risk prioritization while acknowledging that numerical outputs are bounded by expert judgment and observational data rather than statistically derived frequencies (Gritti et al., 2024; Kumaraningrum et al., 2019).

Jetty 1 and Jetty 2 of Integrated Terminal Makassar are fixed marine structures extending from the shoreline into the sea, functioning as dedicated vessel berths for fuel oil loading, unloading, and bunkering operations. Unlike onshore terminal facilities, jetties expose operational crews to open marine conditions including tidal variation, wind, and vessel movement, while constraining available workspace and limiting engineering intervention options. This study focuses on fuel oil bunkering activity at both jetties, covering three operational stages: equipment preparation, transfer execution, and operational completion, each of which concentrates workers, transfer equipment, inter-personnel communication, and the marine environment within a single high-risk workspace.

Primary data were collected through structured field observation over more than two weeks, documenting work sequences, area conditions, equipment usage, hazards, consequences, and existing controls across multiple bunkering cycles at both jetties. Hazard identification results were validated through expert judgment provided by the terminal's safety officer, enabling verification of identified hazards, correction of misclassifications, and confirmation of controls. Secondary data from a systematic literature review conducted prior to fieldwork reinforced the theoretical foundation and method selection.

HIRARC analysis proceeded through hazard identification, risk assessment, and risk control. Likelihood and severity scores were assigned using a five-point ordinal scale adapted from AS/NZS 4360 (Standards Australia & Standards New Zealand, 2004), selected for its established application in occupational risk assessment and compatibility with semi-quantitative field-based scoring (Anthony, 2019; Hutauruk et al., 2026). The likelihood scale is presented in Table 1.

Table 1. Likelihood Scale

Score	Likelihood Criteria	Description
1	Rare	The hazard very rarely occurs under normal operating conditions
2	Unlikely	The hazard may occur, but at a low frequency
3	Possible	The hazard may occur under certain working conditions
4	Likely	The hazard tends to occur frequently during operations
5	Almost Certain	The hazard is very likely to occur repeatedly during operations

The severity scale applied to assess the magnitude of potential consequences is presented in Table 2.

Table 2. Severity Scale

Score	Severity Criteria	Description
1	Insignificant	No injury or significant impact
2	Minor	Minor injury or minor operational disturbance
3	Moderate	Moderate injury or limited operational disruption
4	Major	Serious injury, major damage, or significant contamination
5	Catastrophic	Fatality, severe damage, or extensive environmental contamination

Risk level is determined by multiplying the likelihood score by the severity score, as expressed in Equation (1):

$$RL = L \times S \tag{1}$$

where RL denotes risk level, L denotes likelihood, and S denotes severity. This multiplicative relationship translates the interaction between incident probability and consequence severity into a single prioritization index that guides control selection (Saedi et al., 2014; Zaman et al., 2023). The risk level classification matrix is presented in Table 3.

Table 3. Risk Level Classification Matrix

Likelihood × Severity	Risk Category
1-4	Very low
5-9	Low
10-16	Medium
17-20	High
21-25	Extreme

Following risk assessment, the risk control stage identifies existing controls and evaluates their potential to reduce the final risk level of each identified hazard, following a hierarchy of engineering controls, administrative controls, and personal protective equipment. HAZOP analysis was conducted to deepen HIRARC findings from a process hazard perspective. Activities carrying dominant risk levels in HIRARC were designated as HAZOP nodes, establishing a directional link between the two analytical stages. Each node was analyzed using guide words to identify deviations, then traced to causes, consequences, safeguards, and recommendations. HIRARC–HAZOP integration was operationalized by using HIRARC risk levels as the basis for node selection, then extending those nodes into process deviation analysis. Stefana & Paltrinieri (2020) demonstrated that this form of methodological integration consistently produces more actionable findings than single-method approaches in complex sociotechnical systems. The overall research procedure is organized in Table 4.

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Table 4. Research Procedure (7 stages)

Stage	Activity	Output
1	Observation of bunkering activities at Jetty 1 and Jetty 2	Field data: work sequences, equipment usage, area conditions, and interactions across three stages
2	Hazard identification using HIRARC	Nine identified hazards across preparation, transfer, and completion stages
3	Risk assessment using likelihood and severity	Initial risk matrix: all nine hazards classified as low risk
4	Identification of existing controls	Final risk matrix: residual risk reduced to low or very low per hazard
5	Selection of critical activities/processes	Three nodes designated for process deviation analysis
6	HAZOP analysis on selected nodes	Eight deviations identified with causes, consequences, safeguards, and recommendations
7	Integration of HIRARC and HAZOP findings	Comprehensive risk control proposal linking occupational and process dimensions

Result interpretation emphasized three aspects: dominant hazards, critical process deviations, and the most relevant risk controls for bunkering operations at Jetty 1 and Jetty 2.

RESULTS AND DISCUSSION

HIRARC Result

The HIRARC analysis identified nine primary hazards across three operational stages of fuel oil transfer at Jetty 1 and Jetty 2, spanning both occupational safety and environmental dimensions. Notably, risk is not confined to active fuel flow: hazards are present from the preparation stage and persist through operational completion. Initial risk assessment results are presented in Table 5.

Table 5. Work Process, Hazard Identification, and Initial Risk Assessment

Work Process	Hazard / Aspect	Potential Consequence	Initial Severity	Initial Likelihood	Total Score ($L \times S$)	Initial Risk Level
Preparation of fuel oil transfer equipment	Misunderstanding of work instructions and miscommunication	Injury	3	3	9	Low
Preparation of fuel oil transfer equipment	Back injury during fuel oil hose handling	Injury	3	2	6	Low
Preparation of fuel oil transfer equipment	Slip during hose preparation	Injury	3	2	6	Low
Fuel oil transfer operation	High-pressure flow rate	FUEL OIL hose rupture causing environmental pollution	4	2	8	Low
Fuel oil transfer operation	Damaged hose	Oil spill causing marine pollution	4	2	8	Low

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Work Process	Hazard / Aspect	Potential Consequence	Initial Severity	Initial Likelihood	Total Score ($L \times S$)	Initial Risk Level
Fuel oil transfer operation	Portable radio with low battery capacity	Miscommunication and operational misunderstanding	2	4	8	Low
Fuel oil transfer operation	Slippery deck surface	Crew injury	3	2	6	Low
Completion of transfer operation	Fall hazard during fuel oil hose stowage	Crew injury and property damage	3	2	6	Low
Completion of transfer operation	Oil spill during completion of operation	Oil spill	3	3	9	Low

All nine hazards fall within the low risk category under initial conditions, reflecting the consistent hazard exposure across every stage of bunkering. Likelihood scores were assigned through expert judgment and structured field observation rather than historical incident frequency data, consistent with AS/NZS 4360:2004 practice in settings where incident databases are limited (Saedi et al., 2014; Standards Australia & Standards New Zealand, 2004; Zaman et al., 2023). Two hazards, high-pressure flow rate and damaged hose, carry an initial severity score of 4, reflecting potential for both crew injury and marine environmental contamination. Risk control measures and final risk levels are presented in Table 6.

Table 6. Risk Control Measures and Final Risk Assessment

Work Process	Hazard / Aspect	Risk Control Measures	Residual Severity	Residual Likelihood	Total Score ($L \times S$)	Final Risk Level	Person In Charge	Time Frame
Preparation of fuel oil transfer equipment	Misunderstanding of work instructions and miscommunication	Conduct pre-operation toolbox talk; all crew must attend and comprehend the briefing.	2	2	4	Very Low	All crew	As applicable
Preparation of fuel oil transfer equipment	Back injury during fuel oil hose handling	Use proper lifting techniques during hose handling.	2	1	2	Very Low	All crew	As applicable
Preparation of fuel oil transfer equipment	Slip during hose preparation	Wear complete PPE including anti-slip safety footwear.	2	1	2	Very Low	All crew	As applicable
Fuel oil transfer operation	High-pressure flow rate	Inspect hose and verify valve position pre-transfer; assign minimum two standby crew and maintain continuous communication.	2	1	2	Very Low	All crew	As applicable

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Work Process	Hazard / Aspect	Risk Control Measures	Residual Severity	Residual Likelihood	Total Score ($L \times S$)	Final Risk Level	Person In Charge	Time Frame
Fuel oil transfer operation	Damaged hose	Perform pre-transfer visual inspection; use only certified hoses and confirm equipment readiness.	2	1	2	Very Low	Master, CE, OOW	As applicable
Fuel oil transfer operation	Portable radio with low battery capacity	Verify radio functionality, provide spare batteries, and confirm agreed communication channel prior to operation.	2	1	2	Very Low	All crew	As applicable
Fuel oil transfer operation	Slippery deck surface	Secure hose caps, drain hoses, position drip trays, clean spills immediately, and maintain Shipboard Oil Pollution Emergency Plan (SOPEP) readiness; keep deck dry throughout transfer.	2	1	2	Very Low	All crew	As applicable
Completion of transfer operation	Fall hazard during fuel oil hose stowage	Apply proper lifting methods during hose stowage.	2	1	2	Very Low	All crew	As applicable
Completion of transfer operation	Oil spill during completion of operation	Fully contain residual fuel in hose prior to disconnection and stowage to prevent spill.	2	1	2	Very Low	All crew	As applicable

Following control application, eight hazards were reduced to very low (total score 2) and one, miscommunication, to low (total score 4). The persistence of miscommunication at low rather than very low reflects a structural reality: communication-based hazards are more resistant to control reduction because residual likelihood remains tied to human consistency, not equipment state or procedural sequencing. Field documentation confirms that controls are active components of operational practice, not merely written procedures, evidenced by available oil spill response (OSR) equipment, safety stand down records, and toolbox talk documentation at both jetties.

HAZOP Result

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Building on HIRARC findings, HAZOP analysis traced process deviations at critical points across all three operational stages. Nodes were aligned with HIRARC operational stages, ensuring activity-level hazards could be systematically connected to their process deviation counterparts. The HAZOP worksheet format is presented in Table 7.

Table 7. HAZOP Worksheet Template

Node	Parameter	Guide Word	Deviation	Causes	Consequences	Existing Safeguards	Recommendation
Fuel transfer preparation	Communication	No / Less	Miscommunication	Radio failure, unclear signal	Delay, incorrect action	Briefing, radio check	Backup communication protocol
Fuel transfer process	Flow	More	Excessive flow	Valve error, high pump pressure	Hose rupture, spill	Supervision, flow monitoring	Pressure control and transfer limit
Completion fuel transfer	Residual fuel handling	More	Residual fuel not fully contained	Incomplete draining, improper disconnection, poor stowage practice	Local spill, deck contamination, marine pollution	Hose draining, spill awareness, OSR readiness	Formalize draining and disconnection sequence before stowage

This structure represents the principal component of HAZOP and has been applied extensively to analyze process hazards in oil and gas industries and fuel transfer systems (Fuentes-Bargues et al., 2017; Johnson, 2026; Pérez-Marín & Rodríguez-Toral, 2013). The HAZOP analysis is presented across three node-based tables (Tables 8–10), each corresponding to one operational stage. The construction of these tables followed a systematic procedure: nodes were selected based on the operational stages previously established in the HIRARC assessment, with activities carrying low or higher initial risk levels serving as the basis for node designation. Within each node, parameters were determined by the physical and operational variables most relevant to the transfer process at that stage, including flow, pressure, hose condition, communication, deck condition, and residual fuel handling. Guide words were applied to each parameter following standard HAZOP practice (Chen & Jia, 2015; Johnson, 2026), generating deviations that were then traced to their causes and consequences through structured team analysis informed by field observation data and expert judgment. Existing safeguards were verified against operational documentation and on-site evidence collected during the observation period, and recommendations were formulated where safeguard adequacy was found to be insufficient. Node 1 examines the preparation stage, which is frequently regarded as lower-risk yet carries communication and physical hazard consequences that propagate downstream. The HAZOP worksheet for Node 1 is presented in Table 8.

Table 8. HAZOP Analysis — Node 1: Preparation of Transfer Equipment

Parameter	Guide Word	Deviation	Causes	Consequences	Existing Safeguards	Recommendation
Communication	No / Less	Inadequate communication before operation	Incomplete briefing, unclear signal, low radio readiness	Misunderstanding of task, delayed response, unsafe preparation	Toolbox talk, safety stand down, radio check	Standardize pre-transfer communication checklist and confirmation protocol
Hose handling	More	Excessive manual strain during hose handling	Improper lifting posture, insufficient manpower	Back injury, dropped hose, delayed preparation	Manual handling awareness, crew support	Use lifting aid where possible and assign minimum handling team

Inadequate pre-operation communication increases the probability that hose handling proceeds without clear role assignment, elevating the likelihood of improper lifting posture and physical strain. This cascading relationship is not captured in HIRARC, where both hazards appear as independent entries. The recommended pre-transfer communication checklist therefore functions not only as a communication control but as an indirect safeguard for hose handling safety.

Node 2 is the most hazard-dense stage, encompassing five deviations across pressure, flow, hose condition, communication, and deck condition, as presented in Table 9.

Table 9. HAZOP Analysis — Node 2: Fuel Oil Transfer Operation

Parameter	Guide Word	Deviation	Causes	Consequences	Existing Safeguards	Recommendation
Pressure	More	Excessive transfer pressure	Valve error, blockage, pump setting not controlled	Hose rupture, spill, marine pollution	Hose inspection, standby crew, communication	Establish pressure limit and periodic monitoring during transfer
Flow	More	Excessive flow rate	Improper valve opening, lack of flow control	Overloading hose, overflow, spill event	Pre-transfer inspection, crew monitoring	Apply stepwise opening procedure and flow verification
Hose condition	Other than	Hose not fit for service	Physical damage, hidden wear, non-certified hose	Leak, oil spill, environmental contamination	Visual inspection, certified hose use	Add inspection record and periodic hose integrity verification
Communication	Less	Weak communication during transfer	Low radio battery, channel mismatch, unclear command	Incorrect action, delayed shutdown, unsafe coordination	Radio check, spare battery, agreed channel	Introduce communication confirmation at critical transfer points
Deck condition	Other than	Unsafe or slippery deck	Drip, residual fuel, inadequate housekeeping	Slip injury, slow response during emergency	Drip tray, SOPEP readiness, immediate cleaning	Assign deck watch and housekeeping control during transfer

Pressure and flow deviations share a common consequence pathway toward hose rupture and spill, yet their causes differ in character. Excessive pressure originates from valve and pump control failures, calling for engineering-level intervention such as pressure monitoring instrumentation. Excessive flow is more directly tied to operator valve-opening procedure, making it more amenable to procedural controls such as stepwise opening. Treating both as equivalent and applying only administrative controls would leave the pressure deviation partially unaddressed. Hose condition deviation introduces a further concern: hidden wear and non-certified hose use represent latent failures that visual inspection alone may not reliably detect, pointing toward the need for documented integrity records. Node 3 addresses the completion stage, where residual fuel handling carries direct spill and contamination potential. The HAZOP worksheet for Node 3 is presented in Table 10.

Table 10. HAZOP Analysis — Node 3: Completion of Transfer Operation

Parameter	Guide Word	Deviation	Causes	Consequences	Existing Safeguards	Recommendation
Residual fuel handling	More	Residual fuel not fully contained	Incomplete draining, improper disconnection, poor stowage practice	Local spill, deck contamination, marine pollution	Hose draining, spill awareness, OSR readiness	Formalize draining and disconnection sequence before stowage

Despite containing one deviation, Node 3 carries disproportionate analytical weight. The completion stage is operationally vulnerable because vigilance tends to diminish once active transfer has stopped, a pattern consistent with end-of-task complacency in high-risk industrial operations (Ceylan, 2025). Existing safeguards, hose draining awareness and OSR readiness, address this risk reactively. Formalizing the draining and disconnection sequence as a procedurally mandated step shifts control from individual discipline to structural procedure, a meaningful elevation in reliability. Across all three nodes, process deviations follow the operational logic of the three-stage structure, with Node 2 carrying the highest deviation density and Node 3 presenting the most underestimated residual risk.

Discussion

What the combined HIRARC–HAZOP analysis makes visible is something neither method applied alone could fully articulate: occupational hazards and process deviations in fuel oil transfer operations at Jetty 1 and Jetty 2 are not parallel phenomena but structurally connected ones, where activity-level risk is simultaneously a potential initiating condition for process-level deviation. This reading is consistent with the literature positioning bunkering as a multi-stage, multi-hazard operation in which leakage, equipment failure, and human error converge within the same operational space (Iannaccone et al., 2018; Khan et al., 2025). From the HIRARC perspective, administrative controls dominate the risk reduction portfolio, collectively reducing all nine hazards from low to very low. This outcome warrants critical reading. Risk reduction that rests primarily on human compliance rather than hazard source elimination remains structurally vulnerable to fatigue, time pressure, and inconsistent implementation, a limitation consistently affirmed in the occupational safety literature (Saedi et al., 2014; Siang et al., 2026).

This pattern is worth examining against structurally different settings. Fuentes-Bargues et al. (2017), working in a fixed onshore fuel terminal, documented a control portfolio in which engineering-level interventions occupied a substantially larger proportion of recommended measures, partly because fixed-plant configurations permit infrastructure modification that marine jetty environments do not easily accommodate. The vessel-terminal interface imposes real constraints: physical modifications to jetty structure and transfer equipment are subject to maritime regulatory requirements that make engineering controls substantially more complex to implement than their onshore equivalents. Under these constraints, the administrative layer functions not as a complement to engineering controls but as the primary defense line, precisely the configuration that occupational safety literature identifies as most vulnerable under operational pressure (Saedi et al., 2014). The current control system is functionally sound within this constraint, but requires deliberate reinforcement where administrative reliance is highest. From the HAZOP perspective, hazards that appear as routine work-level risks in HIRARC are revealed to carry deeper process structures: communication failure as a deviation capable of triggering incorrect operational action, and equipment hazards as precursors to flow, pressure, and hose condition deviations directly associated with rupture and spill. These findings align with prior studies identifying communication failure, valve misoperation, hose failure, and spill scenarios as central issues in bunkering and fuel terminal contexts (Ceylan, 2025; Fan, 2024; Fuentes-Bargues et al.,

2017). One finding warrants particular attention because it challenges an assumption rarely questioned in practice. The completion stage is consistently perceived as the lowest-risk phase of bunkering, yet Node 3 reveals a distinct and underestimated risk profile concentrated in residual fuel handling during draining, disconnection, and stowage. The mechanism is behavioral before it is physical. Ceylan (2025) identified diminishing vigilance as structurally recurrent at task transitions in high-risk industrial operations, and bunkering completion represents precisely such a transition: cognitive monitoring load drops before the physical hazard of residual fuel is fully resolved. Existing safeguards address this reactively. Formalizing the draining and disconnection sequence as a procedurally mandated step shifts the locus of control from human discipline, which is vulnerable to complacency, to procedural structure, which is not. Taken together, these findings support the argument that HIRARC–HAZOP integration produces a more complete risk reading than either method in isolation, addressing a gap that prior literature has not explicitly filled within conventional fuel terminal bunkering contexts (Ardiansyah et al., 2026; Pérez-Marín & Rodríguez-Toral, 2013). Bunkering safety cannot be sustained through work discipline alone, nor fully explained through process analysis in isolation, because occupational risk and process hazard ultimately converge within the same operational space.

CONCLUSION

This study demonstrates that fuel oil transfer operations at Jetty 1 and Jetty 2 of Integrated Terminal Makassar carry intertwined occupational and process hazards across all three operational stages. The HIRARC analysis identified nine hazards, all initially classified as low risk and subsequently reduced to low or very low through existing controls that are predominantly administrative in character. The HAZOP analysis revealed that several of these work-level hazards are rooted in deeper process deviations involving communication failure, excessive pressure and flow, hose integrity degradation, slippery deck conditions, and inadequate residual fuel handling at operational completion.

The HIRARC–HAZOP integration proves analytically consequential because it captures what neither method resolves alone: the visible hazards of work activities and the underlying deviations of the transfer process within the same operational system. The safety system currently in place is functionally sound, yet three areas of targeted reinforcement remain necessary. Pre-transfer communication checklists require formalization into standard operating procedure rather than informal guidance, because their dual function as an administrative control in HIRARC and a safeguard layer in HAZOP means inconsistent application creates simultaneous failures at two analytical levels. Hose integrity records require a documentation system beyond visual inspection alone, since latent degradation is precisely the failure mode that inspection-dependent controls miss. The draining and disconnection sequence at operational completion requires procedural mandating because this is where behavioral vigilance declines and residual fuel risk is highest. These refinements are implementable within the existing operational framework of Integrated Terminal Makassar and represent a meaningful step toward a safety management system that does not depend on spontaneous compliance to function reliably.

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