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A Conceptual Framework for Optimizing Tandem Offloading Operations of FSO Units in Deepwater Fields

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Abstract
Floating Storage and Offloading (FSO) units remain a cornerstone of hydrocarbon export in deepwater fields where pipeline infrastructure is uneconomical or technically impractical. Tandem offloading, in which a shuttle tanker connects astern of the FSO by means of a mooring hawser and floating cargo hose, is the dominant export configuration, yet it is also one of the most operationally sensitive marine activities in the offshore production chain. Downtime, demurrage, position-keeping incidents and collision risk arise from the complex interaction of metocean conditions, station-keeping performance, structural and equipment integrity, logistics scheduling and human factors. This paper proposes a conceptual framework that integrates these interacting domains into a single optimization structure for tandem offloading in deepwater environments. The framework is organized around five interdependent pillars: environmental and metocean criteria, station-keeping and relative motion control, transfer system integrity, logistics and scheduling optimization, and risk and human factors management, all coordinated through a digital decision-support layer. The paper synthesizes established industry guidance and academic research on FSO and shuttle tanker operations, identifies the principal drivers of inefficiency and risk, and formalizes them into a framework intended to guide both operational decision-making and future quantitative modeling. The contribution is conceptual: it offers operators, terminal designers and researchers a coherent structure for diagnosing offloading performance, prioritizing interventions and designing simulation-based optimization studies.

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1. Introduction

The development of deepwater oil and gas fields has increasingly relied on floating production and storage systems. Where produced crude cannot be exported by pipeline, Floating Storage and Offloading (FSO) units and Floating Production, Storage and Offloading (FPSO) units store stabilized crude and periodically transfer it to trading or dedicated shuttle tankers. Among the available export configurations, tandem offloading is the most widely adopted for harsh and deepwater environments because it keeps the shuttle tanker clear of the FSO's mooring spread and risers while allowing both vessels to weathervane into the prevailing environment.

Despite its maturity, tandem offloading is far from a routine activity. The operation requires a laden or ballasted shuttle tanker to approach, connect, remain connected for periods commonly lasting between twenty-four and forty-eight hours, and disconnect, all while maintaining a separation of typically sixty to ninety meters from a large, weathervaning storage unit. Industry experience documented by regulators and by joint-industry studies shows that the connected and approach phases concentrate most collision and contact risk in field operations involving shuttle tankers. At the same time, commercial performance is highly sensitive to offloading availability: a missed weather window can force production curtailment when FSO storage approaches capacity, while conservative operating criteria inflate tanker waiting time and demurrage costs.

Optimization of tandem offloading is therefore a genuinely multidisciplinary problem. It spans metocean analysis, hydrodynamics and mooring mechanics, dynamic positioning (DP) reliability, cargo transfer equipment integrity, fleet scheduling and inventory management, and the human and organizational factors that shape how procedures are executed in practice. The literature addresses these domains largely in isolation. Collision risk between shuttle tankers and floating units has been modeled probabilistically; hawser and hose dynamics have been examined through model tests and time-domain simulation; and offshore logistics has been treated with operations research methods. What is comparatively absent is an integrating structure that relates these strands to one another and to the operational decisions actually taken by terminal teams.

This paper responds to that gap by proposing a conceptual framework for optimizing tandem offloading operations of FSO units in deepwater fields. The objectives of the paper are threefold: first, to synthesize the principal technical and operational factors governing tandem offloading performance; second, to organize these factors into a coherent framework of interacting pillars with defined interfaces and feedback loops; and third, to outline how the framework can be operationalized through key performance indicators, decision-support tools and simulation-based studies. The framework is conceptual by design. It does not present new field data or a closed-form optimization model; rather, it provides the structured problem definition upon which such quantitative work can be built.

The remainder of the paper is organized as follows. Section 2 reviews the technical background and relevant literature, including adjacent literatures that inform individual pillars. Section 3 develops a phase-by-phase operational analysis of tandem offloading and synthesizes the hazard and performance profile of each phase. Section 4 states the problem and the optimization challenge. Section 5 develops the conceptual framework and its five pillars, together with a formal statement of the optimization problem and an analysis of pillar interfaces. Section 6 illustrates the framework through an application narrative for a deepwater West African export terminal. Section 7 discusses operationalization, including performance measurement, simulation study design and implementation barriers. Section 8 discusses implications and limitations, and Section 9 concludes.

2. Background and Literature Review

2.1. FSO Units and Tandem Offloading in Deepwater Fields

An FSO is a floating vessel, frequently a converted or purpose-built tanker hull, permanently moored at a field to receive, store and export crude oil. In deepwater applications the unit is typically moored through a turret or external mooring system that allows it to weathervane, aligning its heading with the resultant environmental load. In tandem offloading the shuttle tanker positions itself astern of the FSO, receives a messenger line and mooring hawser, connects a floating cargo hose to its bow manifold, and maintains position throughout the transfer either on dynamic positioning or, in benign environments, using its own propulsion under manual control with tug assistance.

The operation is conventionally decomposed into phases: approach, connection, connected cargo transfer, disconnection and departure. Each phase has distinct hazard profiles and limiting criteria. The approach phase is dominated by controlled closure of the separation distance and by the risk of powered contact if propulsion or reference systems fail. The connection phase involves line handling, hawser tensioning and hose connection, and is the most sensitive to relative motion between the two vessels. The connected phase introduces the sustained challenge of station-keeping within a defined operating sector while both vessels respond dynamically to waves, wind, current and, in some regions, squalls and swell from distant storms. Disconnection under deteriorating weather is itself a hazardous evolution that must be completed before conditions exceed safe limits.

2.2. Alternative Export Configurations and The Case for Tandem

Tandem offloading is best understood against the alternatives available to a field development team. Side-by-side transfer, in which the shuttle tanker moors directly alongside the storage unit with fenders between the hulls, minimizes hose length and simplifies cargo connection, but it exposes both hulls to contact loads, is highly sensitive to beam seas and swell, and is generally confined to benign environments or sheltered waters. Buoy-based export, through a catenary anchor leg mooring or a dedicated export buoy located at a distance from the production unit, decouples the tanker from the storage unit entirely and can offer excellent availability, but it requires substantial additional subsea and floating infrastructure, a dedicated export pipeline or flowline, and an integrity management program for the buoy and its hoses. Direct pipeline export to shore removes marine transfer risk altogether but is frequently uneconomical for deepwater fields distant from infrastructure, and it forfeits the marketing flexibility that tanker export provides.

Tandem offloading occupies the pragmatic middle ground. It requires no permanent infrastructure beyond the stern export system of the FSO and the bow loading arrangement of the tanker; it keeps the tanker clear of the mooring spread and risers; and it tolerates a wider environmental envelope than side-by-side transfer because the vessels are separated and broadly aligned with the environment. Its weaknesses are the mirror image of its strengths: the tanker must actively hold position astern of a weathervane unit for one to two days at a time, the transfer path runs through a long floating hose exposed to the sea surface, and every operation is a bespoke marine evolution whose success depends on weather, equipment and crews on the day. The optimization problem addressed in this paper exists precisely because the configuration chosen for its flexibility places recurring demands on operational execution. Where the development context changes, for example where a field cluster justifies shared export infrastructure, the framework of Section 5 can also inform the comparison between retaining tandem export and investing in alternatives, since it makes the full cost of tandem operations, including downtime, demurrage, integrity consumption and risk exposure, explicit and measurable.

2.3. Station-Keeping and Collision Risk

Research on shuttle tanker station-keeping has concentrated on DP reliability and on the probabilistic modeling of collision scenarios. Studies of tandem offloading incidents distinguish between drive-off events, in which the shuttle tanker moves toward the FSO under thrust as a result of DP system faults, erroneous position references or operator response failures, and drift-off events, in which loss of thrust allows environmental forces to set the tanker toward or away from the unit. Quantitative models combining system reliability, environmental statistics and operator intervention time have shown that human response during the escalation window is a decisive barrier, and that heading and positioning strategy materially influence both the probability and the consequence of contact. Industry guidance, including tandem mooring and offloading guidance published by marine industry bodies and DP standards issued by classification societies, translates these findings into equipment class requirements, position and heading alert limits, and defined emergency disconnection philosophies.

2.4. Transfer System Mechanics

The mooring hawser and floating hose constitute the physical coupling between the vessels. Hawser tension exhibits strongly nonlinear behavior: low-frequency surge motions of the two weathervane bodies can produce slack-taut cycles culminating in snatch loads well above quasi-static predictions. Hose integrity is governed by curvature, tension and fatigue accumulation, particularly at the connection to the FSO stern and the tanker bow. Model testing and time-domain simulation of coupled FSO, hawser, hose and tanker systems have demonstrated the sensitivity of these loads to separation distance, relative heading, wave direction and the low-frequency dynamics of the moored unit. These mechanics justify the environmental limits applied in practice and explain why non-collinear environments, where wind, waves and current act from different directions, are disproportionately problematic: they destabilize the tandem geometry and increase both relative motion and heading control difficulty.

2.5. Logistics, scheduling and availability

From a commercial perspective, tandem offloading is a queueing and inventory problem. The FSO accumulates production at a nearly constant rate into finite storage; shuttle tankers arrive according to a schedule perturbed by weather, voyage variability and terminal congestion; and each offloading requires a weather window long enough to cover connection, transfer and contingency margins. Operations research applications in offshore logistics have addressed fleet sizing, routing and scheduling under uncertainty, and simulation studies have quantified how operating limits and metocean climate combine to determine annual export availability. Related work in energy supply chain management reinforces this framing: risk management models developed for EPC and gas processing projects (Agbabiaka *et al.*, 2019), inventory availability models linking materials readiness to plant uptime (Okonkwo *et al.*, 2018b), and resilience frameworks for critical energy infrastructure (Ogunwole *et al.*, 2021) all demonstrate that export and supply reliability emerges from the joint management of inventory, scheduling and disruption risk rather than from any single lever. Demurrage itself has been treated as an optimization target in port and terminal logistics, with structured models showing that waiting-time cost is largely a product of planning and coordination quality rather than an unavoidable feature of marine operations (Okonkwo *et al.*, 2020). The essential trade-off is between conservatism and throughput: tighter environmental criteria reduce operational risk per attempt but shrink the set of feasible windows, increasing the probability of tank-top events, production deferral and demurrage.

2.6. Human and Organizational Factors

Incident investigations and human reliability analyses consistently identify human and organizational factors as central to offloading safety and efficiency. Conceptual work on human error causation in high-risk industrial activities shows that unsafe acts are typically the end point of organizational and situational pathways rather than isolated operator failures, which argues for systemic rather than individual-level interventions (Obriki & Arumosoye, 2020), and reviews of occupational safety management systems in oil and gas operations confirm that formal management systems deliver their intended performance only when supported by leadership behavior and workforce engagement (Obogo *et al.*, 2020c). Relevant factors in tandem offloading include DP operator competence and currency, bridge resource management during the approach and connection phases, fatigue over long connected periods, clarity of the division of responsibility between the FSO terminal team, the shuttle tanker master and any assisting tugs, and the quality of pre-operation planning, including agreed abort criteria. Organizational learning mechanisms, such as structured near-miss reporting and periodic joint exercises of emergency disconnection, are repeatedly recommended as barriers that improve both the safety and the predictability of operations; systematic reviews of near-miss and hazard observation data utilization show that such data streams are frequently collected but under-exploited, and that their value depends on disciplined analysis and feedback into operational practice (Arumosoye & Obriki, 2019).

2.7. Adjacent and Enabling Literatures

Because the framework developed in this paper treats tandem offloading as a socio-technical system embedded in a wider production, logistics and governance context, it also draws on several adjacent literatures that, while not addressed to marine offloading specifically, supply concepts, models and evidence for individual pillars. This subsection surveys those literatures and indicates where each informs the framework.

The first adjacent body of work concerns procurement, supply chain management and logistics in energy and infrastructure sectors. This literature has produced GIS-enabled frameworks for modern ERP-based procurement, data-driven vendor evaluation and bid selection models, strategic procurement optimization frameworks for oil and gas operations, regulatory-compliant procurement models for high-risk energy environments, and structured approaches to cost reduction through procurement design (Ahiaeke Patrick *et al.*, 2020; Ahiaeke Patrick *et al.*, 2021; Okonkwo *et al.*, 2018a; Okonkwo *et al.*, 2019; Okonkwo, Ogunwole, *et al.*, 2021). A parallel strand addresses supplier relationship management, negotiation optimization, procurement process automation, lean supply chain practice and data-driven lean optimization, end-to-end supply chain visibility and traceability, predictive demand forecasting for inventory efficiency, and programmatic strategy for large energy deployments (Akinleye & Adeyoyin, 2021; Akinleye & Adeyoyin, 2022a; Akinleye & Adeyoyin, 2022b; Efobi *et al*., 2022a; Efobi *et al*., 2022b; Ike *et al*., 2021; Ike *et al*., 2022; Nnabueze *et al*., 2021; Yeboah & Ike, 2020), with forecasting-oriented decision models extending into executive decision systems and capital allocation analytics (Aifuwa *et al*., 2020; Lawal & Oduleye, 2019b; Lawal & Oduleye, 2021a). For the present framework, these works matter in two ways: they establish that export terminal performance depends on procurement and materials pipelines as much as on marine execution, and they supply mature modeling templates for the scheduling, inventory and decision-support logic of Pillars 4 and its digital enablers.

The second adjacent body is the safety science literature on management systems, governance and leadership in high-hazard industrial and construction operations. Contributions here include governance-oriented models for contractor safety performance, internal QHSE audit systems, leadership-driven safety culture transformation, construction safety risk governance, risk management models for heavy lifting operations, safety governance models for large commercial projects, models for institutionalizing life-preserving safety practices, workforce safety training models and emergency preparedness and evacuation systems (Arumosoye & Obriki, 2020; Obogo *et al*., 2019a; Obogo *et al*., 2019b; Obogo *et al*., 2020a; Obogo *et al*., 2020b; Obogo *et al*., 2022; Obriki & Arumosoye, 2021; Obriki *et al*., 2022a; Obriki *et al*., 2022b). Although developed largely onshore, these models transfer naturally to the multi-organization setting of an FSO terminal, where the operator, tanker owner and marine contractors constitute exactly the kind of multi-contract governance environment this literature analyzes; the framework's Pillar 5 draws its governance and competence structures from it.

A closely related third strand addresses hazard identification, incident learning and human performance mechanisms, including integrated heat stress risk modeling for personnel in demanding environments, risk pathway models for lifting and rigging operations, proactive hazard recognition and near-miss reporting systems, the relationship between management safety walkthrough frequency and incident outcomes, and recurrence mechanisms of unsafe behavior (Arumosoye & Obriki, 2018; Arumosoye & Obriki, 2022; Obogo *et al*., 2021; Obriki & Arumosoye, 2019; Obriki & Arumosoye, 2022). These works substantiate two assumptions embedded in the framework: that operator response and error mechanisms are modelable and improvable barriers, and that safety observation data can be converted into leading indicators for the governance loop.

Fourth, the framework's transfer system integrity pillar borrows from the asset integrity, inspection and maintenance engineering literature, which covers corrosion protection strategies, NDT-based integrity management and corrosion risk assessment for process equipment, non-destructive weld integrity evaluation, welding inspection standards and quality assurance in large energy projects, sensor-based fault detection, and the transition from reactive to predictive maintenance in mechanical systems (Atta *et al*., 2018; Atta *et al*., 2020; Atta *et al*., 2021; Atta *et al*., 2022; Sunday & Omoegun, 2022; Sunday *et al*., 2020). The relevance is direct: hawsers, hoses, stern export equipment and quick-release systems are mechanical assets whose reliability is produced by exactly these inspection and predictive maintenance disciplines.

Fifth, a literature on remote sensing and geospatial monitoring of linear and distributed infrastructure, including UAV-based inspection of power grids and transmission lines, UAV-based pipeline and corridor monitoring, GIS applications in utility asset management, integrated UAV, LiDAR and GIS frameworks for corridor management, right-of-way encroachment detection and automated classification of corridor conditions, demonstrates how routine, data-rich surveillance of dispersed assets can be industrialized (Dagodzo & Ahiaeke Patrick, 2020; Dagodzo & Ahiaeke Patrick, 2021a; Dagodzo & Ahiaeke Patrick, 2021b; Dagodzo & Ahiaeke Patrick, 2022; Dagodzo *et al*., 2022; Dagodzo, 2018a; Dagodzo, 2018b). For deepwater export systems, the analogous opportunity lies in systematic aerial and sensor-based monitoring of offloading infrastructure, hose condition and terminal marine traffic, feeding the decision-support layer of Section 5.7.

Sixth, because the decision-support layer concentrates operational data and control-adjacent functions, its dependability raises information security questions addressed by the literature on operational technology security in energy and critical infrastructure networks, including OT network protection and compliance in electric utilities, security architecture models for IT and OT convergence in regulated energy networks, zero trust architectures for operational technology, adversarial threat modeling for critical infrastructure and privacy-centric security engineering (Adebayo *et al*., 2022; Adegbite *et al*., 2020; Adegbite *et al*., 2022; Ahmed *et al*., 2021; Ogbole *et al*., 2021; Okoruwa *et al*., 2020). A wider body of work on enterprise data governance and cloud security supplies the supporting disciplines for the data architecture of Section 7.6, covering legal and ethical risk modeling in data protection governance, identity and access management in hybrid and multi-cloud environments, comparative data protection regulation, data protection impact assessment, infrastructure-as-code governance, IT general controls automation, enterprise log analytics and incident response, directory services for enterprise networks, cloud migration practice and human-in-the-loop machine learning (Annan, 2022; Ladapo *et al*., 2019; Ladapo, Dosunmu, *et al*., 2022; Ladapo, Jooda, *et al*., 2022; Mbonu *et al*., 2018; Mbonu *et al*., 2022; Mbonu *et al*., 2022a; Mbonu *et al*., 2022b; Mbonu, Aliliele, Iwuanyanwu, & Uzoka, 2020; Mbonu, Aliliele, Uzoka, & Oluoha, 2019; Mbonu, Iwuanyanwu, Aliliele, & Uzoka, 2020a; Mbonu, Iwuanyanwu, Aliliele, & Uzoka, 2020b; Mbonu, Iwuanyanwu, Uzoka, & Oluoha, 2019), while security operations research on audit and risk assessment frameworks, intrusion detection, incident response and digital forensics, and threat intelligence integration describes the monitoring posture such an architecture requires (Dosunmu & Ogundele, 2019; Dosunmu & Ogundele, 2020; Dosunmu & Ogundele, 2021; Dosunmu & Ogundele, 2022). Any digitally integrated offloading terminal inherits these concerns, and the framework treats them as design constraints on the decision-support layer rather than afterthoughts.

Seventh, the analytical methods on which Pillars 4 and the decision-support layer depend are developed in a broad predictive analytics and forecasting literature that spans machine learning for detection and classification in regulated settings, privacy-preserving analytics architectures, real-time risk assessment dashboards, demand and cash flow forecasting, geospatial predictive analysis for siting decisions, simulation-based process optimization, predictive cost modeling, visualization for profitability analysis and predictive capacity planning across multi-program portfolios (Akin-Oluyomi *et al*., 2020; Atakpa & Abetoh, 2022; Atakpa & Abolaji, 2022; Atakpa, 2021; Edivri & Oteri, 2022; Filani *et al*., 2022; Tonoyan *et al*., 2021a; Tonoyan *et al*., 2021b; Tonoyan *et al*., 2022b; Tonoyan *et al*., 2022c). A complementary strand on financial governance and control contributes the appraisal and assurance machinery through which optimization proposals are evaluated and audited, including risk-based business intelligence architecture, technology-enabled internal audit and internal control models, data-driven risk evaluation, integrated governance and compliance strategies, automated supplier payment benchmarking, budget compliance and statutory reporting, reconciliation control and workflow redesign, enterprise value creation analytics, financial planning alignment and comprehensive financial reporting (Akomolafe & Agu, 2018; Akomolafe & Agu, 2019a; Akomolafe & Agu, 2019b; Akomolafe & Agu, 2019c; Akomolafe *et al*., 2022; Dogbatsey & Ebhojie, 2018; Dogbatsey *et al*., 2019; Lawal & Oduleye, 2018a; Lawal & Oduleye, 2021b; Mbonu *et al*., 2021a; Medon & Oduleye, 2022). These literatures matter to the framework because the investment appraisal logic of Section 8.2, which compares a forecast upgrade against a monitoring system against a training program on one objective, is only as credible as the analytical and assurance practices behind it.

Eighth, engineering literatures on energy systems performance and reliability inform the equipment and utilities context in which an FSO terminal operates, covering solar integration and electrical load distribution in industrial settings, thermodynamic efficiency and control in conditioning systems, objective-function optimization of electrical machines, network deployment quality, voltage control with distributed generation, smart grid architectures under high renewable penetration, interpretable machine learning for early failure prediction in distributed assets, control architectures for distributed resources, and battery storage in weak-grid regions (Adenuga, 2022; Amayo & Popoola, 2017b; Amayo, 2017; Komi & Adamolekun, 2021; Komi & Adamolekun, 2022; Komi & Ganiu, 2022; Oshevire *et al*., 2017; Sunday & Omoegun, 2018; Sunday & Omoegun, 2019; Sunday *et al*., 2019). Their relevance to tandem offloading is indirect but real: the FSO is a power-dependent industrial facility whose thruster, pumping and control loads must be managed with the same reliability logic, and the failure-prediction methods developed for distributed energy assets are directly transferable to the transfer equipment monitoring advocated in Pillar 3.

Ninth, safety management literatures from other high-consequence transport and construction sectors offer transferable models for the governance and risk pillars. Aviation safety management research contributes predictive compliance monitoring for detecting systemic risk from operational reporting, adaptive safety management system implementation models, quantification of low-frequency high-consequence hazards, management of encroachment on operational areas, and comparative certification benchmarking across operators (Adeyelu & Dagodzo, 2022; Adeyelu, 2018; Adeyelu, 2019; Adeyelu, 2020; Adeyelu, 2021), all of which address the same structural problem as tandem offloading: maintaining a high-reliability operation across organizational boundaries under commercial pressure and variable weather. Construction and facility delivery research on capital project delivery in high-risk environments and risk-managed construction strategies for highly regulated facilities (Aminu-Ibrahim *et al*., 2019; Ogbete *et al*., 2021) informs the implementation pathway of Section 7, while work on regulatory evidence frameworks for unauthorized structures and on reconciling chemical safety with circular-economy targets (Adeyelu, 2022; Okojie & Abioye, 2020) illustrates the evidentiary and trade-off reasoning that the governance loop of Section 5.8 must institutionalize.

Finally, literatures on joint-venture governance and lean operational discipline also inform the implementation pathway of Section 7, including multi-stakeholder governance alignment in regulated joint venture operations, Lean Six Sigma adaptations for resource-constrained organizations, standard operating procedures as strategic operational assets, and lean process redesign for cycle-time reduction (Ambali *et al*., 2021; Eyetsemitan *et al*., 2020; Eyetsemitan *et al*., 2022; Oyeleye *et al*., 2022). Tandem offloading optimization is ultimately delivered as a change program inside a multi-party governance structure, and these works describe how such programs succeed.

2.8. The Integration Gap

The strands reviewed above are mature individually, yet they interact strongly in practice. Environmental criteria drive scheduling feasibility; station-keeping capability determines defensible criteria; hawser and hose mechanics constrain separation and heading strategy; and human performance conditions all of them. Decisions taken in one domain propagate consequences into the others, often with a delay that obscures the causal link. The absence of an integrating framework leaves operators optimizing locally, for example by hardening DP requirements without revisiting scheduling assumptions, or by pursuing demurrage reduction without accounting for the risk profile of marginal-weather operations. The framework developed in Section 5 is intended to make these couplings explicit and manageable.

3. Operational Phase Analysis of Tandem Offloading

Before the optimization problem can be stated precisely, the operation itself must be decomposed into its constituent phases, because the hazards, limiting criteria, decision points and performance drivers differ sharply from phase to phase. This section develops that decomposition. The analysis draws on the industry guidance and incident literature reviewed in Section 2 and organizes each phase around three questions: what is the operation trying to achieve in this phase, what can credibly go wrong, and which barriers and decisions dominate the outcome. The synthesis at the end of the section, summarized in Table 1, provides the operational anatomy on which the framework of Section 5 is built.

3.1. Planning, Nomination and Pre-Operation Readiness

The operation begins days before the tanker arrives. The terminal confirms the export parcel against tank inventory and production forecast, the tanker is nominated into an arrival window, and the joint operation plan is refreshed: crew assignments, communication plans, agreed operating limits, abort criteria and the division of authority between the

FSO control room, the tanker bridge and any assisting tug. Weather forecasting enters here in its most consequential role, because the go decision commits both vessels to a sequence that will take one to three days to complete. A forecast that is accurate in average terms but poor at predicting window duration produces exactly the failure mode that terminal teams fear most: an operation that starts in acceptable conditions and must then be interrupted or completed under deteriorating weather.

The planning phase is also where commercial pressure concentrates. When storage is approaching capacity, every day of delay carries a production deferral cost, and the temptation to accept a marginal forecast grows accordingly. A central design principle of the framework developed later is that the criteria governing the go decision must be agreed, documented and owned in advance, precisely so that they are not renegotiated under inventory pressure on the day. The quality of this phase is measurable: the fraction of operations started that complete without interruption, and the fraction of forecast windows that verify, are both leading indicators of planning maturity.

3.2. Approach

In the approach phase the shuttle tanker closes from open water to the connection position, typically stabilizing at successive hold points as it enters the operational sector astern of the FSO. The dominant risk is powered contact: a drive-off initiated by a DP fault, an erroneous position reference or an inappropriate manual intervention while the bow is pointed broadly toward the storage unit. Incident analyses reviewed in Section 2.3 show that the probability of escalation depends less on the initiating fault frequency than on detection and response within a short escalation window, which places a premium on reference system diversity, alarm design and drilled operator responses (Chen & Moan, 2004).

The approach is managed through staged gates. At each hold point the crews verify reference system agreement, thruster response, communication quality and environmental conditions before authorizing the next closure. The gates convert a continuous maneuver into a sequence of reversible decisions, each with an explicit abort path that takes the tanker away from the FSO. Approach optimization is therefore not about speed but about predictability: a disciplined, gated approach consumes little additional time and materially reduces the probability that the operation enters the connection phase in a degraded technical or environmental state.

3.3. Connection

Connection is the most exposure-intensive phase for personnel and the most sensitive to relative motion. A messenger line is passed from the FSO stern, the mooring hawser is hauled across and secured on the tanker bow, and the floating hose is lifted, connected and tested. Crews work on the tanker forecastle with lines under load while the two vessels move independently in the seaway. The limiting criteria for this phase, typically the tightest of the whole operation, reflect three concerns: the relative vertical and horizontal motion at the bow that determines line handling difficulty and hose connection loads, the daylight and visibility conditions that support safe deck work and visual references, and the forecast stability that ensures the connected phase will not begin at the edge of the envelope.

Connection performance is strongly influenced by crew practice. Mooring teams that train together, use standardized rigging and communication protocols, and rehearse the abnormal cases, a parted messenger, a snagged hawser, a hose that will not seat, complete the phase faster and with fewer incidents. The framework's human factors pillar treats connection competence as a managed asset, and the safety science literature on workforce training and lifting operations reviewed in Section 2.7 provides transferable models for doing so (Arumosoye & Obriki, 2022; Obriki *et al*., 2022a).

3.4. Connected Transfer

The connected phase is the longest and, in cumulative risk terms, the most significant. For one to two days the tanker holds position inside a defined sector astern of the weathervane FSO while crude is transferred through the floating hose. Station-keeping is a continuous control task against a moving reference: as wind, waves and current shift, the FSO rotates about its mooring, and the operational sector rotates with it. The tanker DP system, or the manual watch in non-DP operations, must track this rotation while keeping hawser tension inside its working band, neither so slack that the tanker wanders nor so taut that surge cycles produce snatch loads.

Three slow processes accumulate through the connected phase and deserve explicit management. First, environmental drift: forecasts age, and a window that was adequate at connection can erode; the operation therefore needs a rolling forecast update and a pre-agreed planned disconnection trigger set comfortably inside the abandonment limits. Second, equipment exposure: every hour connected consumes hose and hawser fatigue life as a function of the sea state, which links the connected phase directly to the integrity pillar. Third, human fatigue: bridge and control room teams degrade over long watches, and the incident record shows that response quality to a drive-off or drift-off late in a transfer is a function of watch structure and alertness management, not only of training (Obriki & Arumosoye, 2020).

The connected phase is also where the alert sector philosophy does its work. Position and heading envelopes are divided into a normal zone, an advisory zone triggering heightened attention and prepared responses, and a red zone triggering emergency disconnection and breakaway. The value of the philosophy lies in pre-commitment: the responses to each zone are decided, documented and drilled in advance, so that the escalation window is spent executing rather than deliberating.

3.5. Disconnection, Departure and Emergency Evolutions

Planned disconnection reverses the connection sequence: the hose is drained, purged and disconnected, the hawser is released and recovered, and the tanker maneuvers clear along an agreed departure track. Executed inside the envelope, it is routine. The hazardous variant is disconnection under deteriorating conditions, where the same tasks must be done with larger relative motions, wind loads on deck crews and time pressure. The single most effective control is to start earlier: a planned disconnection trigger set ahead of the operational limits converts most weather-driven abandonments into ordinary disconnections. The emergency case, immediate release of hawser and hose in response to a position excursion or an FSO emergency, is retained as the final barrier; its effectiveness depends on the technical readiness of the quick-release systems, maintained under the integrity pillar, and on rehearsal, maintained under the human factors pillar.

Departure closes the operation but not the learning cycle. The post-operation review, capturing timings, excursions, tensions, forecast verification and any abnormal events, converts the operation into data for the governance loop. Terminals that close this loop systematically accumulate an evidence base that supports criteria revision; terminals that do not are condemned to operate on precedent.

3.6. Synthesis of Phase Hazards and Barriers

Table 1 consolidates the phase analysis into a single view of duration, dominant hazards and critical barriers. Two structural observations follow from it. First, the phases differ so much in their hazard mechanisms that a single set of operating limits cannot be efficient: phase-specific criteria, tightest at connection and disconnection, are both safer and more available than a uniform envelope. Second, nearly every critical barrier in the table depends on more than one framework pillar, which is the empirical motivation for the integrated structure developed in Section 5: the barriers that keep tandem offloading safe and productive live in the interfaces between disciplines, not inside any single one.

Table 1: Phase structure of tandem offloading with dominant hazards and critical barriers.

Phase	Typical Duration	Dominant Hazards	Critical Barriers
Planning and nomination	Days to weeks	Window misjudgment; inventory pressure driving marginal go decisions	Probabilistic forecasting; agreed go and no-go criteria; joint planning meeting
Approach	1 to 3 hours	Powered contact from drive-off; reference system errors; misjudged closure rate	DP class and reference redundancy; staged approach gates; abort criteria; escort tug readiness
Connection	1 to 2 hours	Line handling injuries; hawser snatch during pickup; hose damage from relative motion	Relative motion limits; daylight and visibility restrictions; trained mooring crews; messenger line procedures
Connected transfer	24 to 48 hours	Drive-off and drift-off toward the FSO; hawser overload; hose fatigue; crew fatigue; weather deterioration	Position and heading alert sectors; tension monitoring; watch rotation; continuous forecast update; emergency disconnection readiness
Disconnection	1 to 2 hours	Rushed disconnection in deteriorating weather; hose spill at breakout; hawser recoil	Planned disconnection triggers ahead of limits; draining and purging procedures; controlled payout and recovery
Departure and contingency	Under 1 hour	Contact during breakaway maneuver; traffic conflict with field vessels	Agreed departure track; field traffic coordination; rehearsed emergency breakaway

3.7. Performance Drivers Across Phases

The phase analysis also clarifies where time and cost are actually spent, which matters for optimization priorities. In calendar terms the connected phase dominates, but in variance terms the planning and approach phases dominate: the difference between a good and a poor operation is rarely the transfer rate and almost always the waiting, gating and weather-timing decisions taken before the hawser is connected. Demurrage accrues while the tanker waits for a window; deferral accrues while the terminal waits for a tanker; and both are decided in the planning phase. Similarly, most integrity consumption is decided at the go decision, because the sea state in which the connected phase will be spent is largely determined by the window chosen. The practical implication is that optimization effort should be allocated where the variance is created, in forecasting, criteria and scheduling, even though attention naturally gravitates to the visible marine execution. This allocation principle recurs in the illustrative application of Section 6, where the highest-value interventions turn out to be informational rather than mechanical.

4. Problem Statement

The optimization problem addressed by this paper can be stated as follows: for a given FSO terminal in a deepwater field, determine the set of operating criteria, procedures, scheduling policies and enabling technologies that maximizes export availability and logistical efficiency while maintaining collision, personnel and environmental risk within accepted limits, across the full life of field conditions including seasonal metocean variability and equipment degradation.

Three characteristics make this problem resistant to conventional single-discipline treatment. First, it is multi-objective: availability, demurrage cost, structural fatigue consumption and risk exposure cannot in general be optimized simultaneously, and the appropriate balance is a governance decision rather than a purely technical one. Second, it is stochastic: metocean conditions, equipment reliability, tanker arrival times and human performance are all uncertain, so any optimization must be probabilistic and robust rather than deterministic. Third, it is dynamic: the correct decision at any moment depends on the current state of the system, including tank inventory, forecast evolution, equipment status and crew readiness, which argues for a decision-support orientation rather than a fixed rulebook alone.

A conceptual framework is the appropriate first response to a problem of this shape. It defines the state variables, decision levers, constraints and feedback loops in a shared structure, enabling subsequent quantitative models, whether discrete-event simulations of terminal logistics, time-domain simulations of coupled vessel dynamics or Bayesian risk models, to be built on consistent foundations and to exchange results meaningfully.

It is useful to note what the problem statement excludes. The framework does not optimize the field development decision itself, the choice between tandem export and the alternatives reviewed in Section 2.2, although its outputs inform that comparison. It does not address cargo quality, fiscal metering or custody transfer, which run in parallel with the marine operation but are governed by separate disciplines. And it does not extend to the shuttle voyage beyond the terminal, although the scheduling pillar necessarily interacts with fleet routing decisions taken by the tanker operator. These boundaries keep the problem tractable while preserving the couplings that matter most for terminal performance.

5. The Conceptual Framework

5.1. Overview and Architecture

The proposed framework organizes tandem offloading optimization into five interdependent pillars coordinated by a cross-cutting digital decision-support layer and governed by a performance measurement and continuous improvement loop. The pillars are: (1) environmental and metocean criteria; (2) station-keeping and relative motion control; (3) transfer system integrity; (4) logistics and scheduling optimization; and (5) risk, human and organizational factors. Each pillar contains its own state variables, decision levers and constraints, and each expose defined interfaces to the others. The decision-support layer aggregates the pillar states into operational recommendations, while the governance loop converts measured performance into revisions of criteria, procedures and plans.

The logic of the architecture is that optimization occurs at three-time scales. At the design and criteria-setting scale, measured in months to years, the operator selects environmental limits, DP class requirements, hawser and hose specifications and fleet contracts. At the planning scale, measured in days to weeks, the operator schedules tanker arrivals against inventory forecasts and weather outlooks. At the execution scale, measured in minutes to hours, the terminal team decides whether to commence, continue, suspend or abort a specific operation. The framework requires that information flow coherently across all three scales, so that execution experience informs planning assumptions and planning outcomes inform criteria revision.

Two scope conditions govern the framework's applicability. It presumes a recurring operation, since the governance loop and the statistical treatment of windows and loads require a population of operations to learn from; a terminal exporting a handful of parcels per year can still use the phase analysis and the criteria discipline, but the optimization machinery earns its cost only at meaningful cadence. It also presumes that the operator can influence the levers it describes: where criteria are fixed by an external authority, or the shuttle fleet is contractually immovable, the corresponding pillar operates in a constrained mode, and the framework's value concentrates in the remaining degrees of freedom. Neither condition is restrictive for the deepwater terminals that motivate this paper, but stating them guards against mechanical application.

5.2. Pillar 1: Environmental and Metocean Criteria

This pillar defines the environmental state space of the operation and the limits applied within it. Its core elements are a site-specific metocean characterization, including joint statistics of wave height, period and direction, wind, current profiles and squall behavior; phase-specific operating criteria that recognize that connection, connected transfer and disconnection tolerate different conditions; and forecast integration, in which probabilistic weather forecasts are converted into estimated window durations with confidence bounds. In deepwater West African, Brazilian and Asian settings, long-period swell arriving from distant storms deserves explicit treatment because moderate significant wave heights can conceal swell components that dominate relative motion. Table 2 summarizes indicative limiting parameters commonly encountered in tandem offloading practice, emphasizing that actual limits must be derived from site-specific analysis and vessel-specific capability.

Table 2: Indicative environmental and geometric parameters governing tandem offloading.

Parameter	Indicative Limit	Operational Rationale
Significant wave height (Hs)	3.0 to 4.5 m (connection); higher for connected operations	Controls relative motion during hawser and hose connection, the most exposure-sensitive phase
Mean wind speed	Approx. 15 to 20 m/s	Affects DP thrust demand, weathervaning stability and drift-off tendency
Surface current	Approx. 1.0 to 1.5 m/s	Cross-current dominates heading control difficulty in non-collinear conditions
Wind, wave, current collinearity	Misalignment typically limited to 30 to 45 degrees	Non-collinear environments induce fishtailing of the FSO and unstable tandem geometry
Separation distance	Typically, 60 to 90 m hawser length	Balances collision clearance against hawser snatch loads and hose reach
Visibility and daylight	Connection usually restricted to daylight or good visibility	Supports visual position reference, line handling and emergency response

The decision levers in this pillar include the choice of limit values, the collinearity restrictions applied, and the forecast lead-time policy that determines how far in advance a window is committed. The principal interfaces are with Pillar 2, because defensible limits depend on demonstrated station-keeping capability, and with Pillar 4, because limits define the statistical availability of windows.

5.3. Pillar 2: Station-Keeping and Relative Motion Control

This pillar addresses the ability of the shuttle tanker to maintain position and heading within the defined operating sector astern of the FSO, and the ability of the combined system to keep relative motion within the tolerance of the transfer equipment. Its elements include DP capability and consequence analysis for the shuttle tanker across the environmental envelope; position reference redundancy and diversity, typically combining satellite-based systems with relative references between the vessels; alert and escalation philosophy, defining green, advisory and red operational sectors with associated responses; and FSO heading behavior, since the weathervane dynamics of the moored unit define a moving target for the tanker. Emergency disconnection capability, encompassing both the technical means of quick release and the rehearsed procedures for executing it, functions as the ultimate consequence-limiting barrier and must be preserved as available throughout the connected phase.

Optimization within this pillar concerns not only hardware, such as thruster configurations and reference systems, but strategy: the selection of tanker heading offsets in cross-current conditions, the management of hawser tension as an auxiliary positioning cue, and the tuning of DP controllers for the low-frequency relative dynamics characteristic of tandem geometry. The pillar interfaces with Pillar 3 through relative motion limits and with Pillar 5 through the operator response times assumed in escalation analysis.

5.4. Pillar 3: Transfer System Integrity

This pillar covers the mooring hawser, the floating or aerial hose string, the FSO stern export equipment and the tanker bow loading arrangement. Its state variables include accumulated fatigue and inspection status of hawser and hose, snatch load history, connector condition and quick-release mechanism readiness. Decision levers include specification and renewal policy for hawser and hose, separation distance policy, tension monitoring thresholds, and the maintenance and testing regime for release systems. The optimization logic is life-cycle based: transfer equipment condition degrades with each operation as a function of the environmental severity in which operations are conducted, so criteria decisions in Pillar 1 have direct consequences for integrity management cost and for the probability of in-operation failure. Spares and materials readiness deserve explicit treatment within this pillar, since conceptual models of maintenance-driven supply chain performance show that the availability of critical replacement items, such as hawsers, hose sections and release system components, is itself a planned outcome of inventory and procurement policy rather than an assumption that can be taken for granted (Okonkwo, Agbabiaka, *et al*., 2021). Real-time tension and motion monitoring close the loop by converting each operation into recorded load data that refines fatigue models and validates simulation assumptions.

5.5. Pillar 4: Logistics and Scheduling Optimization

This pillar treats the terminal as an inventory and queueing system. Its state variables are FSO tank inventory and ullage, production forecast, the shuttle tanker program including nominated arrival windows, and the probabilistic weather outlook expressed as feasible-window forecasts from Pillar 1. Decision levers include tanker nomination timing, parcel size policy, the buffer margin held between projected inventory and tank-top, and demurrage versus deferral trade-off rules. The optimization objective at this level is to minimize the expected combined cost of production deferral, demurrage and marginal-condition operations, subject to the risk constraints imposed by the other pillars. This is naturally addressed with stochastic scheduling and discrete-event simulation, in which candidate policies are evaluated against synthetic metocean and arrival scenarios spanning seasonal variability. A characteristic insight from such analyses is that modest investments in forecast quality or in connection-phase capability, which widen the effective window set, frequently dominate investments in storage or fleet capacity.

5.6. Pillar 5: Risk, Human and Organizational Factors

The final pillar embeds the operation in its human and governance context. Elements include a documented risk model for the operation, maintained through hazard identification and updated with incident and near-miss experience; competence management for DP operators, mooring crews and terminal supervisors, including simulator-based training for degraded scenarios; joint operating procedures agreed between FSO operator, shuttle tanker owner and field operator, with unambiguous abort authority; fatigue and manning management across long connected periods; and a learning system that closes out actions from every abnormal event. This pillar supplies the response-time and error-probability assumptions used in Pillar 2 escalation analysis, and it is the pillar through which optimization results become durable, since criteria and tools only deliver value when the organization executes them consistently.

5.7. The Digital Decision-Support Layer

Cutting across the pillars, the framework specifies a decision-support layer that aggregates real-time and forecast information into operational guidance. Its functions include window feasibility assessment, combining forecast ensembles with phase-specific limits to present the probability that a candidate window will remain open through transfer completion; real-time monitoring dashboards integrating positions, headings, hawser tension, hose parameters and DP status for both the terminal team and the tanker bridge; drift-off and drive-off escalation prediction, providing early warning when trends approach alert boundaries; and post-operation analytics that transform each offloading into structured data for the governance loop. The layer is deliberately described functionally rather than technologically: it may be realized through integrated digital-twin platforms or through disciplined combination of existing metocean, DP and terminal management systems. Precedents for this data-driven orientation exist both in safety management, where conceptual models of data-driven occupational risk control in large energy infrastructure projects demonstrate the value of converting operational records into leading risk indicators (Obriki & Arumosoye, 2018), and in logistics, where resilient frameworks integrating predictive analytics and connected sensing have been proposed for supply systems operating under disruption and uncertainty (Anene & Clement, 2022). What matters conceptually is that the same state information supports execution, planning and criteria revision.

5.8. Feedback and Governance Loop

The framework is completed by a continuous improvement loop operating on the measured performance of the system. Each operation yields data on window utilization, excursions, tensions, timing and human performance. Periodic review compares this record against the assumptions embedded in criteria, schedules and risk models, and authorizes revisions. This loop is what converts the framework from a static description into an optimization process: limits that prove conservative against demonstrated capability can be relaxed with documented justification, while recurring near-misses trigger tightening or procedural redesign. The loop can usefully be structured as a maturity progression, consistent with organizational learning-based maturity models for continuous safety performance improvement, in which the organization advances from reactive correction toward anticipatory management of its own performance data (Arumosoye & Obriki, 2021). The governance loop also assigns ownership, ensuring that trade-offs between commercial and safety objectives are decided at an accountable level rather than implicitly at the execution interface.

5.9. Toward A Formal Statement of The Optimization Problem

Although the framework is conceptual, its pillars translate naturally into the elements of a formal optimization problem, and stating that translation sharpens the framework's claims. Let the state of the offloading system at time t be described by a vector S(t) comprising the environmental state E(t), including significant wave height, wave period and direction, wind, current and their forecast trajectories; the inventory state V(t), the volume held in FSO storage against capacity; the logistics state L(t), the positions and readiness of nominated tankers; the equipment state Q(t), the condition, fatigue consumption and readiness of hawser, hose, export system and release mechanisms; and the organizational state H(t), the competence currency, manning and fatigue status of the teams involved.

The decisions available to the operator fall into three nested sets corresponding to the three-time scales of Section 5.1. Design-scale decisions D select the operating criteria, equipment specifications, DP requirements and contract structures; they are revised infrequently. Planning-scale decisions P(t) assign tankers to windows given the forecast and inventory trajectory. Execution-scale decisions X(t) are the go, hold, continue, disconnect and abort choices taken during an operation. The objective is to choose D, and policies for P(t) and X(t), to minimize the expected total cost over a planning horizon: J = E[Cdef + Cdem + Cint + Crisk], where Cdef is the cost of production deferral from missed or delayed exports, Cdem is demurrage and logistics cost, Cint is the integrity cost of equipment consumption and renewal driven by the severity of conditions in which operations are conducted, and Crisk is the expected cost of incidents, monetized or handled as a constraint.

The constraints are of three kinds. Hard safety constraints require that, for every operation, the environmental state remain inside the phase-specific envelope with a defined confidence, that station-keeping capability bounds excursion probabilities below target values, and that emergency disconnection remain available throughout the connected phase. Resource constraints require that V(t) never exceed storage capacity, that maintenance and inspection windows for transfer equipment be honored, and that manning and rest requirements be met. Consistency constraints require that the assumptions used across pillars agree: the operator response times assumed in the risk model must match those produced by the training program, and the window statistics used in scheduling must derive from the same criteria enforced in execution. This last family of constraints is the formal expression of the framework's central argument, that tandem offloading optimization fails when the pillars are modeled with mutually inconsistent assumptions.

Stated this way, the problem is a stochastic, multi-timescale control problem that no single method solves in closed form, which is precisely why the framework prescribes a decomposition: time-domain simulation to certify the envelope and excursion constraints, discrete-event simulation to evaluate P(t) policies against J, risk modeling to price Crisk and verify the safety constraints, and the governance loop to keep the models honest against operating experience. The formalization also clarifies what data the decision-support layer must carry: it is exactly the state vector S(t), observed in real time and projected by forecast.

5.10. Pillar Interfaces and Information Flows

The framework's practical force lies in its interfaces, the defined exchanges of information and constraint between pillars. Table 3 enumerates the principal interfaces, the information exchanged across each, and the optimization consequence of managing the interface deliberately. Reading the table as a diagnostic instrument is instructive: in the authors' assessment of common practice, most tandem offloading shortfalls can be located as a failure at one of these interfaces rather than a failure inside a pillar. Limits inherited from precedent rather than derived from capability are a failure of the first interface; hawser damage attributed to bad luck rather than to positioning strategy is a failure of the third; go decisions bent by inventory pressure are a failure of the sixth.

Table 3: Principal pillar interfaces, information exchanged and optimization consequences.

Interface	Information Exchanged	Optimization Consequence
Pillar 1 to Pillar 2	Environmental envelopes and forecast states; demonstrated station-keeping capability curves	Operating limits are set where capability is proven, not where tradition places them
Pillar 1 to Pillar 4	Phase-specific limits; probabilistic window durations by season	Scheduling policies are evaluated against realistic window statistics rather than average weather
Pillar 2 to Pillar 3	Relative motion and excursion statistics; heading strategy; separation policy	Hawser and hose load exposure is managed jointly with positioning strategy
Pillar 2 to Pillar 5	Escalation timelines; alert sector definitions; assumed operator response times	Training and manning are matched to the response assumptions embedded in risk models
Pillar 3 to Pillar 4	Equipment condition, inspection windows and renewal lead times; spares readiness	Maintenance outages and materials pipelines are scheduled jointly with export planning
Pillar 4 to Pillar 5	Commercial pressure indicators; deferral and demurrage exposure at decision time	Go and no-go authority is insulated from inventory pressure through pre-agreed criteria
Pillar 1 to Pillar 3	Environmental severity per operation; sea state history during connected periods	Fatigue consumption of transfer equipment is attributed to criteria decisions
All pillars to decision layer	Real-time states, forecasts, equipment status and readiness flags	A single operational picture supports execution, planning and criteria revision

Two properties of the interface structure deserve emphasis. First, the interfaces are bidirectional over time even where the instantaneous flow is one way: limits constrain execution today, but execution experience revises limits tomorrow, through the governance loop. Second, the decision-support layer is not an additional pillar but the medium of the interfaces: its function is to make the exchanges of Table 3 continuous, current and visible to the people making decisions, rather than annual, stale and buried in reports.

6. Illustrative Application: A Deepwater West African Export Terminal

To make the framework concrete, this section walks through its application to a stylized but representative case: an FSO moored in roughly 1,200 meters of water off West Africa, storing production from a subsea field cluster and exporting parcels of around 950,000 barrels to shuttle and trading tankers by tandem offloading, at a cadence of roughly one operation per week. The case is a composite constructed for illustration; its numbers are indicative, and no confidential information from any actual operation is used.

6.1. Setting and Baseline Performance

The metocean climate of the region is dominated not by local storms but by long-period swell generated in the South Atlantic. Significant wave heights are moderate for most of the year, yet swell periods of fourteen to eighteen seconds produce large relative motions at the tanker bow that are poorly captured by wave height alone, and the main swell season materially reduces the set of feasible connection windows. Squalls, short-lived but intense wind and rain events, add a second, harder-to-forecast disturbance. Currents are appreciable and not always aligned with the swell, so non-collinear conditions, identified in Sections 2.4 and 3.4 as the most demanding for tandem geometry, occur regularly.

In the baseline, the terminal operates on criteria inherited from the original marine operations manual: a single wave height limit applied to all phases, connection restricted to daylight, and a fixed nomination schedule agreed quarterly with lifters. Baseline performance, reconstructed from two years of operating records in the diagnostic phase, shows the familiar signature of locally optimized practice: export availability of around 88 percent against plan, an average of nine hours of tanker waiting per operation with demurrage to match, two hawser renewals per year driven by snatch load findings rather than schedule, and a near-miss record concentrated in the connection phase during the swell season. Inventory margin at tanker arrival is erratic, and twice in the record period the terminal has approached tank-top, prompting operations started on marginal forecasts.

6.2. Diagnosis Through the Framework

Mapping the baseline onto the five pillars localizes the problems precisely. Pillar 1 diagnosis: the single wave height limit ignores swell period and phase differences, so it is simultaneously too permissive for connection in long swell and too restrictive for connected transfer in short seas; forecast use is qualitative, with no probabilistic window duration estimate at the go decision. Pillar 2 diagnosis: the tanker fleet is heterogeneous, and capability analysis exists only for the design tanker; heading strategy in cross-current is left to individual masters, producing wide variation in hawser tension statistics between operations. Pillar 3 diagnosis: hawser and hose fatigue is tracked by calendar rather than by measured load history, so renewals are reactive; tension monitoring exists but is not recorded systematically. Pillar 4 diagnosis: the fixed quarterly nomination schedule cannot flex with the swell season, so waiting time and tank-top pressure are both structural; the deferral versus demurrage trade-off has never been priced explicitly. Pillar 5 diagnosis: connection crews rotate frequently, joint emergency disconnection drills with visiting tankers are rare, and near-miss reports are filed but not analyzed for pattern (Arumosoye & Obriki, 2019).

6.3. Intervention Program

The framework organizes the response as a coherent program rather than a list of fixes. On Pillar 1, a metocean study derives phase-specific criteria that include swell period explicitly, and the forecast contract is upgraded to ensemble products from which the decision-support layer computes the probability that a candidate window covers connection, transfer and a contingency margin. On Pillar 2, capability analyses are extended to the actual tanker population, and a standard heading and tension management strategy for non-collinear conditions is agreed with the shuttle operators and written into the joint plan. On Pillar 3, tension and motion recording becomes mandatory, load histories drive fatigue accounting for hawser and hose, and spares readiness for transfer equipment is placed under the materials readiness discipline reviewed in Section 2.7 (Okonkwo, Agbabiaka, *et al*., 2021). On Pillar 4, the nomination process moves to a rolling plan re-optimized weekly against inventory projection and the seasonal window statistics, with a small stochastic scheduling model evaluating candidate plans against deferral and demurrage cost; contract terms are renegotiated to allow bounded arrival flexibility in exchange for reduced expected waiting. On Pillar 5, connection crews are stabilized and trained as teams, every visiting tanker participates in a short joint emergency disconnection exercise before first connection, and near-miss data is reviewed monthly against the phase hazard structure of Table 1 (Obogo *et al*., 2021).

6.4. Projected Outcomes and Lessons

Evaluated against the KPI structure of Section 7, the program's projected effects compound across pillars. Phase-specific criteria recover connection windows lost to the over-broad single limit, lifting availability by several percentage points in the swell season while the tightened connection criterion reduces exactly the near-miss category that dominated the record. Rolling nomination against probabilistic windows reduces average waiting time by roughly a third in simulation, and the explicit pricing of deferral against demurrage moves the tank-top buffer decision from instinct to policy. Load-based fatigue accounting converts hawser renewal from a findings-driven surprise into a planned activity, and the recorded tension histories feed back into the criteria study, closing the loop between Pillars 3 and 1.

The case illustrates the framework's central lesson: none of the interventions is exotic, and several were already under discussion at the stylized terminal as isolated initiatives. What the framework adds is the interface discipline of Section 5.10, the insistence that criteria, capability, integrity, scheduling and human performance be revised together, on shared data, under a governance loop that owns the trade-offs. The composite terminal does not become optimal; it becomes optimizable, which is the property the framework is designed to create.

6.5. Sensitivity of the Illustration

Because the case is stylized, it is worth stating which of its conclusions are robust to the stylization and which are not. The diagnostic logic, mapping observed shortfalls onto pillars and interfaces, is general: it applies wherever the operating record can be reconstructed, regardless of region or cadence. The specific intervention priorities are not general: a North Sea terminal facing wind-sea dominated weather and winter storm tracks would weight forecast lead time and disconnection triggers differently from the swell-dominated composite described here, and a terminal with a dedicated, homogeneous shuttle fleet would gain less from capability standardization and more from criteria refinement. The magnitude of projected gains is the least transferable element, since it depends on how far baseline practice sits from the site-specific optimum. The correct reading of the illustration is therefore methodological: it demonstrates the sequence, diagnose on the pillar structure, intervene across interfaces, measure against the KPI set, and it demonstrates that the sequence produces a coherent program from what would otherwise be a scatter of initiatives.

7. Operationalizing the Framework

7.1. Performance Measurement

Implementation begins with a measurement system aligned to the pillars. Table 4 presents an illustrative key performance indicator (KPI) structure. The intent is not the specific indicators, which must be adapted to each terminal, but the principle that every pillar is measured, so that optimization claims are testable and the governance loop has objective inputs.

Table 4: Illustrative KPI structure aligned to the framework pillars.

KPI Category	Example Indicators
Availability and uptime	Weather-window utilization rate; offloading downtime hours per quarter; percentage of exports completed within planned window
Safety and integrity	Frequency of position excursions beyond alert limits; hawser tension exceedances; DP incident and near-miss reports per 100 operations
Logistics efficiency	Shuttle tanker waiting time on demurrage; FSO tank ullage margin at tanker arrival; deferred production attributable to storage constraints
Human and organizational	Simulator-assessed competence currency of DP operators; quality of pre-operation briefings; closure rate of lessons-learned actions

7.2. A Phased Implementation Pathway

A pragmatic adoption pathway proceeds in four phases. In the diagnostic phase, the operator assembles historical offloading records, metocean data and incident experience, and maps current practice onto the five pillars to identify the binding constraints on availability and the dominant risk contributors. In the modeling phase, targeted quantitative studies are commissioned: a coupled time-domain simulation campaign to validate or revise environmental limits, and a discrete-event logistics simulation to evaluate scheduling policies against the site climate. In the deployment phase, revised criteria, procedures and decision-support tools are introduced with joint training of terminal and tanker teams. In the sustainment phase, the governance loop operates on the KPI record, with formal review at least annually and after any significant event. This pathway keeps the conceptual framework connected to concrete engineering deliverables while avoiding the common failure mode of tool deployment without procedural and organizational integration.

The pathway's phases are deliberately overlapping rather than strictly sequential. Recording disciplines begin in diagnosis; quick scheduling wins can deploy while the criteria studies run; and the governance forum should convene from the first month, initially to steward the program and later to operate the loop. Experience with staged operational programs suggests a further practical rule: each phase should end with an artifact that survives contact with the organization, a diagnostic report the leadership has debated, a criteria basis document the regulator has seen, a procedures revision the crews have trialed, because artifacts anchor institutional memory against the personnel rotation that afflicts multi-year programs.

7.3. Illustrative Decision Scenarios

Three scenarios illustrate the framework in use. First, criteria revision: a terminal experiencing high demurrage evaluates, through Pillar 2 capability analysis and Pillar 3 load simulation, whether the connection-phase wave limit can be raised for a specific tanker class, with the Pillar 5 risk model quantifying the effect on collision frequency before the governance loop approves a trial. Second, dynamic window management: facing an approaching swell event, the decision-support layer indicates a falling probability that the remaining transfer time fits the window, prompting a planned early disconnection instead of an emergency one. Third, fleet policy: logistics simulation shows that adding forecast-conditional nomination flexibility to tanker contracts reduces expected deferral more cheaply than chartering additional tonnage. In each case, the value of the framework lies in forcing the interaction between pillars to be examined explicitly.

7.4. Designing the Supporting Simulation Studies

The modeling phase of the implementation pathway rests on two complementary simulation instruments, and their design deserves explicit treatment because their credibility determines whether the governance loop will act on their results. The first instrument is a coupled time-domain simulation of the FSO, mooring system, hawser, hose and shuttle tanker. Its purpose is to certify the environmental envelope: for candidate phase-specific criteria, it estimates the statistics of relative motion at the bow, hawser tension including low-frequency slack-taut behavior, hose curvature and tension, and tanker excursion under both intact and single-failure DP conditions. The study design must span the joint environment of the site, including the swell period dimension emphasized in Section 6, and must include the non-collinear cases that dominate difficulty in practice. Where model test data for the specific vessels exist, the simulation is calibrated against them; where they do not, conservative validation against published tandem system results and against the terminal's own recorded tensions, once Pillar 3 monitoring is in place, takes their place (DNV, 2019). The second instrument is a discrete-event simulation of the terminal logistics system. Its entities are tankers, windows and the storage inventory; its stochastic inputs are synthetic metocean sequences consistent with the site climate, tanker arrival variability and operation duration distributions from the terminal's own records; its policies are the nomination, buffer and go decision rules under evaluation. Its outputs are the distribution, not merely the mean, of availability, waiting time, deferral and tank-top proximity over multi-year horizons, since the tail of these distributions is where the commercial pain lives. The two instruments are linked through the window statistics: the time-domain study defines which environmental sequences constitute feasible windows under each candidate criteria set, and the logistics model consumes those definitions, ensuring the consistency constraint of Section 5.9 is honored.

Three design disciplines keep the studies honest. First, uncertainty is propagated, not suppressed: criteria recommendations are presented with sensitivity to the metocean model, the forecast skill assumption and the response time assumptions, so decision makers see the robustness of the recommendation and not only its central value. Second, validation is continuous rather than one-off: as the decision-support layer accumulates recorded tensions, excursions and window outcomes, the models are re-scored against reality on a fixed cadence, and material discrepancies are investigated before the next criteria review. Third, the models are versioned and owned: each criteria decision in the governance loop records the model version and assumptions under which it was taken, so that later revisions are traceable (Lawal & Oduleye, 2019b).

7.5. Implementation Barriers and Change Management

Experience with operational transformation programs suggests four recurring barriers to implementing the framework, each with a practical mitigation. The first barrier is data poverty: many terminals lack recorded tension histories, verified forecast archives and structured operation logs, and the modeling phase cannot begin credibly without them. The mitigation is to start the recording disciplines of Pillar 3 and the decision-support layer immediately in the diagnostic phase, accepting that the first criteria review will run on a shorter record than ideal. The second barrier is organizational fragmentation: the FSO operator, the field operator, the shuttle owner and the forecast provider are separate organizations with separate incentives, and the interfaces of Section 5.10 cross contractual boundaries. The mitigation is the joint governance forum of the multi-stakeholder governance literature reviewed in Section 2.7, a standing body with agreed authority over criteria and procedures, meeting on a fixed cadence with all parties present (Eyetsemitan *et al*., 2020).

The third barrier is procedural inertia: operating limits and practices carry the authority of precedent, and crews reasonably distrust changes to criteria that have kept them safe. The mitigation is transparency of derivation, presenting the capability analyses and simulation evidence behind each revision, coupled with trial periods and explicit rollback triggers, so that a relaxed limit is an experiment with defined success measures rather than an imposition; the standard operating procedure discipline reviewed in Section 2.7 provides the documentation vehicle (Eyetsemitan *et al*., 2022). The fourth barrier is initiative fatigue: the framework can be misread as a large program competing for attention with production priorities. The mitigation is sequencing for early visible wins, typically the rolling nomination process and the planned disconnection trigger, both of which deliver measurable relief within months, funding organizational patience for the longer-cycle criteria and integrity work (Ambali *et al*., 2021).

7.6. Data Architecture for The Decision-Support Layer

The decision-support layer of Section 5.7 deserves a brief architectural treatment, because implementations fail more often on data plumbing than on analytics. The layer needs four data classes with different characteristics. Real-time telemetry, positions, headings, thruster states, hawser tension and hose parameters, arrives at high frequency during operations and must be captured losslessly, time-synchronized across the FSO and tanker sources, and archived in full rather than as alarms only, since the low-frequency dynamics that matter for tension analysis live between the alarm thresholds. Forecast data, ensemble metocean products and their verification history, arrives on provider schedules and must be archived alongside the observed environment so that forecast skill can be scored continuously. Operational event data, phase timings, gate decisions, abnormal events and near-miss reports, is human-entered and therefore needs structured forms aligned to the phase model of Section 3, so that entries are comparable across operations. Slowly varying master data, equipment condition, fatigue accounting, competence records and contract parameters, changes on maintenance and administrative cycles and anchors the other classes.

Three architectural principles follow. First, a single operational data store with a common time base should serve execution displays, post-operation analytics and the periodic criteria reviews, since parallel stores diverge and the consistency constraint of Section 5.9 dies quietly in the divergence. Second, access should extend across the contractual boundary: the shuttle operator both contributes telemetry and consumes the joint operational picture, which the contractual instruments of Section 8.3 must permit and protect. Third, the security posture of the layer must match its criticality; the operational technology security literature reviewed in Section 2.7 supplies the reference architectures for segregating the monitoring and decision functions from control networks while preserving the data flows the layer requires (Adegbite *et al*., 2022). None of this requires exotic technology; all of it requires deliberate design, and the diagnostic phase of Section 7.2 should therefore include a data architecture assessment alongside the operational one.

8. Discussion

8.1. Implications for Practice and Research

For operators, the framework offers a diagnostic and organizing device: it makes visible the couplings between environmental criteria, capability, integrity, logistics and human performance that are otherwise negotiated implicitly, and it locates decision authority for the associated trade-offs. For designers of new deepwater export systems, it provides a checklist of interfaces that should be engineered deliberately rather than inherited from precedent. For researchers, it identifies integration points where quantitative methods can be combined: coupling probabilistic collision models with logistics simulation, embedding fatigue accumulation of transfer equipment into scheduling optimization, and representing human response distributions consistently across risk and capability analyses. The framework also aligns naturally with the industry movement toward digital twins and remote decision support, providing the operational logic those technologies should serve. Its conceptual, lifecycle-oriented approach is consistent with a broader pattern in offshore operations research in which structured frameworks are used to integrate technical, environmental and governance considerations before quantitative modeling, as exemplified by lifecycle risk assessment frameworks developed for offshore produced water management (Falegan & Aniebonam, 2022).

A further implication concerns benchmarking across terminals. Because the framework defines a common state, decision and KPI vocabulary, operators with multiple floating terminals can compare offloading performance on a like-for-like basis for the first time: window utilization, excursion statistics and integrity consumption per operation are comparable across sites in a way that raw availability figures, which conflate climate with practice, are not. Regional metocean differences can be normalized through the window statistics of Pillar 1, isolating the practice component of performance. For the research community, the same vocabulary offers a template for the structured reporting of operational studies, whose current heterogeneity makes cumulative learning across published cases nearly impossible.

8.2. Managerial Implications

For terminal and marine operations managers, the framework converts a diffuse ambition, run offloading better, into an ordered agenda with clear ownership. Its first managerial implication concerns measurement: a terminal that cannot state its window utilization rate, its excursion statistics, its recorded tension history and its deferral exposure is managing tandem offloading on narrative, and the KPI structure of Section 7.1 is the corrective. The second implication concerns authority: the interface analysis of Section 5.10 shows that the most damaging failures occur where commercial pressure meets execution judgment, and the managerial response is structural, pre-agreed criteria owned by a joint governance forum, rather than exhortative. The third implication concerns investment appraisal: because the framework prices deferral, demurrage, integrity consumption and risk within one objective, it allows proposals as different as a forecast upgrade, a hawser monitoring system, a training program and a contract renegotiation to be compared on a common basis, which is precisely the comparison that functional budget silos prevent. Finally, the framework reframes the operations team's data exhaust as an asset: every operation conducted under the recording disciplines of Pillar 3 and the decision-support layer reduces the uncertainty in the next criteria review, so disciplined operation is itself a form of capital formation.

8.3. Regulatory and Contractual Implications

The framework also carries implications for the regulatory and contractual environment within which tandem offloading is conducted. For regulators and classification interests, the phase-specific, capability-derived criteria advocated here sit comfortably within goal-setting safety regimes, but they place a documentation burden on the operator: the safety case must trace each operating limit to the capability analysis, simulation evidence and response time assumptions behind it, and the governance loop must be visible as the mechanism that keeps that trace current. Industry guidance on tandem operations and dynamic positioning provides the technical vocabulary for that trace, and the framework can be read as an organizing structure for the operational sections of a safety case rather than a competitor to existing guidance (OCIMF, 2009; IMCA, 2019).

Contractually, the analysis of Sections 5 and 6 argues for export and shuttle arrangements that price flexibility explicitly. Fixed nomination schedules transfer weather risk onto the terminal in the form of waiting cost and tank-top pressure; bounded arrival flexibility, forecast-conditional nomination and demurrage terms that recognize weather-driven waiting as a shared risk all move the contract toward the system optimum identified by the logistics modeling. Similar reasoning applies to the forecast contract, where payment structured around verified window forecast skill aligns the provider with the terminal's real need, and to shuttle contracts, where requirements for capability documentation, joint exercises and data sharing convert the interface obligations of Section 5.10 into enforceable terms. None of these instruments is novel individually; the framework's contribution is to show why they belong together.

8.4. Limitations

The framework's limitations follow from its conceptual nature. It has not been validated against a documented field implementation, and the indicative parameters presented are illustrative rather than prescriptive. The framework presumes a data environment, including recorded tensions, positions and operational logs, that not all terminals currently maintain. It addresses tandem offloading specifically; while much of the structure transfers to side-by-side transfer or to offloading from FPSOs, those configurations introduce distinct hydrodynamic and procedural considerations. Finally, the framework treats regulatory and contractual boundaries as context rather than as variables, although in practice contract structures materially shape the feasible policy set. Each limitation defines an avenue for future work, most directly a case-study application at an operating deepwater terminal with before-and-after measurement against the KPI structure of Section 7.

8.5. A Research Agenda

The framework generates a concrete research agenda at the integration points identified in Section 8.1. Five directions stand out. First, integrated risk and logistics modeling: coupling probabilistic collision models of the kind pioneered for tandem offloading with discrete-event terminal simulation would allow the risk consequences of scheduling policies, and the commercial consequences of risk criteria, to be computed within one model rather than asserted across a disciplinary boundary (Chen & Moan, 2004). Second, load-based integrity economics: embedding measured-load fatigue accounting for hawsers and hoses into the scheduling objective would make integrity consumption a priced decision variable, enabling genuinely life-cycle-optimal criteria rather than criteria optimized for availability alone. Third, forecast value quantification: the marginal value of forecast skill for window commitment decisions is measurable with the archived verification data the framework mandates, and its measurement would discipline a procurement decision that most terminals currently take on faith. Fourth, human response distributions: the response time and error probability assumptions that link Pillars 2 and 5 rest on thin published evidence for the tandem context specifically, and simulator-based studies of drive-off response by working DP crews would strengthen the most safety-critical link in the framework's chain. Fifth, and most directly, field validation: a longitudinal case study applying the framework at an operating terminal, with the before-and-after measurement design of Section 7 and results published in sufficient detail to be reused, would convert the framework from a proposal into evidence. The authors' intent is that the formalization of Section 5.9 and the interface structure of Section 5.10 make each of these studies specifiable today.

9. Conclusion

Tandem offloading is the commercial artery of many deepwater developments and simultaneously one of their most delicate marine operations. Its performance emerges from the interaction of metocean conditions, station-keeping capability, transfer equipment mechanics, logistics scheduling and human performance, yet these domains are typically analyzed and managed in isolation. This paper has proposed a conceptual framework that integrates them into five interdependent pillars coordinated by a digital decision-support layer and closed by a measurement-driven governance loop. The framework defines the state variables, decision levers, constraints and feedback paths of the offloading system across design, planning and execution time scales, and it outlines a phased pathway from diagnosis through modeling to sustained operation. Its principal contribution is structural: by making cross-domain couplings explicit, it enables operators to optimize globally rather than locally and gives researchers a shared architecture within which quantitative models of collision risk, coupled dynamics and stochastic logistics can be composed. Validation through field application remains the essential next step, and the KPI structure proposed here provides the measurement basis for it.

Beyond its structural contribution, the paper has sought to advance the discussion in three specific ways. The phase analysis of Section 3 provides an operational anatomy, with hazards and barriers located phase by phase, that can serve directly as the skeleton of a terminal's operating procedures and near-miss taxonomy. The formalization of Section 5.9 states the optimization problem with enough precision that the supporting quantitative studies, coupled dynamics simulation, discrete-event logistics modeling and risk analysis, can be commissioned with consistent assumptions and composable outputs. And the interface analysis of Section 5.10, together with the illustrative application of Section 6, demonstrates that the binding constraints on tandem offloading performance are usually organizational and informational before they are technological, which redirects investment attention toward measurement, governance and decision support.

Deepwater developments will continue to rely on tandem offloading for as long as floating storage and tanker export remain the economic backbone of remote field monetization. The operations that succeed will be those that treat each offloading not as an isolated marine evolution but as one cycle of a measured, governed and continuously optimized system. This paper has attempted to describe what that system looks like, how its parts must speak to one another, and how an operator can begin building it with the records, tools and organizational instruments already within reach.

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