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Engineering Design Optimization of Floating Production, Storage, and Offloading Facilities for Improved Safety and Production Reliability

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Abstract
Floating production, storage and offloading facilities combine hydrocarbon processing, crude storage, accommodation and marine operations on a single motion-exposed hull, so that layout, mooring, storage and equipment decisions jointly determine personnel risk, production availability and capital cost. This study formulates FPSO concept design as a three-objective optimization problem in six design variables: separation between process and accommodation, inter-module gap, compression train configuration, storage capacity, mooring concept and blast wall rating. Coupled safety, production and cost models capture congestion-driven explosion overpressure, wall escalation, accommodation impact, offloading and collision risk, k-out-of-n compression availability, motion-induced process upsets, stochastic offloading deferral and hull and deck sizing. The NSGA-II algorithm produced a 160-design Pareto front, and designs were selected with TOPSIS under balanced, safety-led and cost-led preferences. Relative to a conventional reference design, the balanced design reduced potential loss of life by 59 percent and raised production availability by 2.5 percentage points for a 12.6 percent increase in capital cost, and it outperformed the reference design in every one of 3,000 parameter-uncertainty samples. Wider inter-module gaps and higher blast wall ratings controlled risk more efficiently than greater separation distance, and two 100 percent compression trains dominated three or four smaller trains. A turret-moored concept was selected under all preferences and became decisive in a harsh-environment case.

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1. Introduction

Floating production, storage and offloading (FPSO) facilities are the dominant development concept for deepwater and remote oil fields, including the Brazilian pre-salt, West Africa, the North Sea and Southeast Asia, because they combine processing, storage and export on a single hull and avoid the need for export pipelines [1, 2]. Their design differs fundamentally from that of fixed platforms. Process equipment, utilities, accommodation, cargo tanks, turret or spread mooring and offloading systems share a confined deck that moves with the sea, and the hull dimensions, storage volume and topsides arrangement are interdependent [3, 4]. A decision to widen the gaps between process modules to reduce explosion congestion lengthens the deck and the hull, a decision to increase storage volume changes the offloading interval and the hull size, and a decision to adopt a turret rather than spread mooring changes vessel motions, offloading operability and capital cost [5–7].

The consequences of FPSO design choices have been demonstrated by accidents. The explosion on FPSO Cidade de São Mateus in 2015 killed nine people and highlighted how gas accumulation in confined spaces can escalate [8], and analyses of FPSO casualty records show that fires, explosions, hydrocarbon releases, collisions and offloading incidents are recurring accident types [9, 10]. Studies of FPSO fire and explosion risk, gas dispersion and blast wall response confirm that layout and congestion strongly influence consequences [11–14], while studies of ship and shuttle tanker collision demonstrate the importance of marine operations to overall risk [15–17]. At the same time, production availability determines the commercial performance of the unit, and it is affected by equipment redundancy, vessel motions, offloading delays and the outages that follow major incidents [18–20], and it also depends on the condition of hull and export equipment exposed to corrosion in the marine environment [21].

Design optimization offers a means to address these interactions systematically. Optimization methods have been applied extensively to FPSO hull dimensions [6, 22], mooring systems [23–25] and risers [26–28], and to topsides layout and weight [29–31]. However, these studies usually optimize one subsystem for cost or structural performance, and safety and production reliability are treated as constraints or are assessed afterwards [32, 33]. Risk assessment studies, conversely, evaluate the safety of a given design rather than searching for better designs [10, 34]. There is therefore a need for an integrated approach that represents the principal safety and reliability mechanisms explicitly and searches the design space for designs that are good on all objectives at once.

This study develops such an approach. It formulates FPSO concept design as a three-objective optimization problem in which potential loss of life (PLL) and capital expenditure are minimized and production availability is maximized. Six design variables represent the principal concept-stage decisions: separation between process and accommodation, inter-module gap, compression train configuration, storage capacity, mooring concept and blast wall rating. Coupled safety, production and cost models are solved by the NSGA-II algorithm, and preferred designs are selected by TOPSIS under different stakeholder preferences and then tested for robustness to parameter uncertainty and for sensitivity to a harsher metocean environment. The paper contributes a transparent, reproducible formulation of FPSO design trade-offs, evidence on which design levers control risk most efficiently, and a demonstration of how the preferred design changes with environment. Section 2 reviews the literature, Section 3 presents the methodology, Section 4 the results, Section 5 the discussion and Section 6 the conclusions.

2. Literature Review

This section reviews the literature on the design, safety and reliability of FPSO facilities that bears on concept-stage optimization. It covers FPSO concepts, conversion and hull design (Section 2.1), mooring, riser and turret design optimization (Section 2.2), topsides layout, weight and motion effects (Section 2.3), fire, explosion and dispersion safety (Section 2.4), collision, offloading and escape, evacuation and rescue (Section 2.5), production availability, maintenance and integrity (Section 2.6) and human and organizational factors in operational safety (Section 2.7). Section 2.8 identifies the research gap. The literature on optimization methods for floating systems, which has grown rapidly through floating wind research, is drawn on where its methods transfer to FPSO design [32, 33].

2.1. FPSO Concepts, Conversion and Hull Design

FPSOs evolved from tanker conversions in the 1970s and 1980s, and their state of the art has been reviewed repeatedly [1, 35]. Paik and Thayamballi provided a comprehensive treatment of ship-shaped offshore installations covering design, building and operation [3], the FPSO design and construction guidance manual set out lessons from early projects [4], and offshore standards set out safety principles, design against accidental loads and the design of station-keeping systems [36–38]. Reviews of ultra-deepwater production technologies place FPSOs among the competing floating concepts [2]. A substantial body of conference literature documents conversion practice, including North Sea conversions [39], design improvements for twenty years of operation without docking [40], very large conversions [41], conceptual design of deep-sea FPSOs from VLCCs [42], practical conversion experience [43, 44], low-cost conversions for Brazilian fields [45], the Mystras conversion [46] and tanker selection criteria [47]. Structural modifications for cargo tank integrity [48], bracket design under fatigue [49] and tank arrangement optimization [5] address hull design detail.

Hull dimension optimization has become an active research area. Lee and colleagues optimized FPSO hull dimensions for Brazilian fields using stability and motion criteria and extended the approach to multi-objective optimization [6, 22],. Cylindrical hull forms have also been proposed as alternatives to ship-shaped hulls, notably for FLNG vessels on which the effect of safety gaps and blast wall layout on dispersion and explosion has been examined [50, 51]. Motion response prediction from model tests and numerical analysis [52], multibody dynamics of ships and offshore structures [53] and green water susceptibility in the North Sea [54] define the hydrodynamic constraints on hull design. Hull fatigue and corrosion govern life extension, with studies of spectral fatigue validated against full-scale West African measurements [55], feedback from in-service inspections [56], structural longevity [57], integrity management of a Malaysian FSO [58], wave model applicability to fatigue assessment [59], the ultimate strength of corroded hulls [60] and corrosion management and material selection for crude oil export equipment in marine service [21]. Energy optimization of FPSO processing over field life [61, 62], carbon footprint reduction through optimization of the FPSO process [63] and flare-gas recovery technologies that return otherwise wasted gas to fuel or export [64] show that hull and topsides decisions also govern energy and environmental performance.

2.2. Mooring, Riser and Turret Design Optimization

Mooring and riser systems have received more optimization research than any other FPSO subsystem. Genetic algorithms were applied to mooring pattern optimization early in the field's development [23, 24], and particle swarm optimization was introduced and improved for mooring design [65, 66], drawing on developments in particle swarm methods more generally [67–69]. Evolutionary and integrated design methodologies [25, 70] and parametric studies of line design variables [71, 72] followed. Multi-objective optimization with NSGA-II coupled to a vessel-mooring model [73], surrogate-assisted multi-objective genetic algorithms [74] and Kriging metamodels for long-term extreme response [75] have reduced the computational cost of searching large design spaces.

Floating wind research has contributed a multi-objective screening tool for taut synthetic mooring systems [76] and reviews of the optimization methodologies used in floating platform design [32], and advances in metaheuristic algorithms for structural design [77] provide further transferable techniques.

Mooring reliability and integrity are central to safety. Industry surveys have documented past mooring failures and degradations [78], and studies have analysed transient effects of broken lines [79, 80], mooring fatigue [81], design loads in harsh environments [82], the effect of line layout on loads [83], and large truncated mooring dynamics [84]. Damage detection using recurrent neural networks [85] and standards such as API RP 2SK and ISO 19901-7:2019 [38, 86] frame design practice. Integrated mooring and riser design was advocated in the 1990s [87–89] and developed in studies of integration and coupled analysis [90–93], including the P-43 and P-48 FPSOs [94] and ultra-deepwater systems [95]. Riser design has been optimized for fatigue and configuration [26, 96–99], including steel lazy wave risers optimized with artificial intelligence tools and managed with Bayesian machine learning [27, 100], flexible risers in shallow water [101], subsea production riser systems [102] and Bayesian optimization of riser configurations [28], and dynamic umbilicals have been optimized with approximate models [103]. Turret-moored FPSOs have been analysed through coupled dynamic analysis [7], moonpool effects [104], the Terra Nova turret system [105], automated optimization of internal turret mooring [106] and scantling optimization of the turret structure [107].

2.3. Topsides Layout, Weight and Motion Effects

Topsides layout determines both congestion and separation, and it has been optimized using mathematical programming and expert systems. Ku and colleagues developed multi-floor and module layout optimization for LNG FPSO liquefaction processes [29, 108], Kim and colleagues proposed topside arrangement methods based on expert systems and optimization and evaluated feasibility indices [109, 110], and Lee and colleagues reported an optimal layout case study for an LNG FPSO [30]. Baalisampang and colleagues developed an inherently safer layout for FLNG liquefaction and showed how equipment congestion affects LNG release consequences [111, 112]. Weight estimation models for FPSO topsides based on genetic programming, nonlinear regression and work breakdown structure [31, 113, 114], design optimization of an FPSO water injection module [115] and surrogate-based optimization of deck support frames [116] connect layout to hull sizing. Integrated engineering environments for process FEED of offshore facilities support these studies [117]. Structural optimization methods developed for offshore wind and jacket structures [118–122] and reviews of ship structural design optimization [33] provide further methods.

Vessel motions affect process performance, which is a distinctive concern for floating facilities. Early experimental work showed that irregular motion degrades absorption and distillation processes [123, 124], and later studies examined packing types under tilt and motion [125], tower motion effects on packing efficiency [126], marinization of mass transfer columns for FLNG [127], and dividing-wall columns for FLNG [128], while CFD-driven design of fluid-particle separation and filtration equipment offers a route to separators that tolerate motion [129]. Sloshing in tanks has been treated in theoretical monographs [130, 131], and experiments show that liquid in cargo tanks influences the wave response of FLNG vessels [132]. These studies show that motion-induced loss of separation and treating efficiency is a real production penalty that differs between mooring concepts.

2.4. Fire, Explosion and Dispersion Safety

Fire and explosion are the dominant process hazards on FPSOs. Suardin and colleagues assessed fire and explosion on FPSOs [11], Jin and Jang performed probabilistic fire risk analysis and structural safety assessment of topside modules [12], Kim and colleagues analysed nonlinear structural consequences under fire [133] and fire load application with passive fire protection [134], and Kang and colleagues studied explosion-induced blast wall responses [13]. Wang and colleagues analysed vapour cloud explosion risk with domino effects [14]. Probabilistic explosion risk analysis of topside process areas [135], explosion structural response procedures [136], accidental limit state design of thin-walled structures [137], water spray mitigation and stochastic explosion risk on ultra-deepwater semi-submersibles [138, 139], VCE risk in FLNG modules [140] and LNG floating storage and regasification QRA [141] extend the evidence. Studies of cylindrical FLNG vessels have shown that safety gaps between modules reduce dispersion and explosion consequences [50, 142] and that blast wall layout can be optimized [51].

Design guidance for fire and blast loading [143], accidental loads [37] and safety principles and arrangements [36] codify design responses. Blast wall performance has been studied through pulse pressure testing [144], finite element analysis of profiled panels [145] and assessment of existing walls in well-test areas [146]. Gas dispersion modelling using data-driven methods [147], integrated fire, explosion and combustion product modelling [148], dynamic Bayesian prediction of platform fire probability [149], dropped object analysis for LNG-FPSO topsides [150] and improved FMEA of FPSO processing systems [151] address specific hazard mechanisms. Analyses of hydrocarbon leaks on the Norwegian shelf have identified root causes, failure models during maintenance and the role of leak verification as an operational barrier [152–155], and process release frequency data underpin QRA [156]. Safety assessment methodologies for marine systems [157], the treatment of assumption deviation in QRA [158], offshore risk assessment principles [34] and major hazard risk indicators [159] complete the methodological base. The safety of FPSO and FLNG topside processing has been reviewed as a distinct challenge [10].

2.5. Collision, Offloading and Escape, Evacuation and Rescue

Marine operations add risks absent from fixed installations. Risk assessment of FPSOs with emphasis on collision [15], a literature review of ship-FPSO collision risk [16], risk assessment of ship collisions against offshore structures [160], probabilistic approaches for powered vessel collisions [161] and Brazilian collision statistics [162] define the frequency side. Structural studies have addressed collision resistance of ship-shaped structures [163], collision scenarios and probabilistic damage [164], tubular structure responses [165], impact mechanics [166], damaged tanker side panels [167], energy dissipation in jacket collisions [168], work hardening and strain-rate effects [169], FPSO collision damage and platform behaviour [170, 171], hull collapse risk [172] and hull damage reliability under bow impact [173]. Tandem offloading

has been analysed in the time domain [174], and shuttle tanker collision risk has been summarized by the UK regulator [17], predicted through relative motion [175] and addressed by online decision support [176].

Side-by-side offloading, used particularly for FLNG, has been studied extensively for hydrodynamic interaction [177–183], current practice [184], connection system dynamics [185], and side structure crashworthiness [186]. Hawser material selection and extreme tension assessment [187, 188], offloading operability criteria [189], cargo transfer vessels in Brazil [190], LNG-FPSO offloading performance [191], weakest-failure-mode reliability of offloading systems [192], risk-based assessment of relative motion [193] and dynamic risk and resilience of offloading [194, 195] show that offloading is both a safety and an availability concern. Escape, evacuation and rescue (EER) studies have estimated the probability of successful EER in Arctic and harsh environments [196, 197], prioritized human and organizational factors [198, 199], simulated personnel during emergencies [200–202], compared human reliability models [203], analysed experience from offshore accidents including Deepwater Horizon [204, 205], developed frameworks for evacuation human error [206], assessed EER system reliability [207], examined safety requirements for evacuation systems [208] and determined human error probabilities during musters [209]. These results show that accommodation location relative to hazards affects both exposure and the success of evacuation.

2.6. Production Availability, Maintenance and Integrity

Production availability modelling for offshore facilities uses Monte Carlo simulation and stochastic Petri nets. Aven's early evaluation of oil and gas production and transportation systems [210], Monte Carlo approaches for multi-state systems and offshore installations [20, 211], stochastic Petri net evaluation [212], FPSO-specific production availability models [18, 19], availability of air compression and nitrogen systems on LNG-FPSOs [213], availability with age-based maintenance [214], reconfigurable multi-state systems with interdependencies [215], dynamic Bayesian assessment of safety-critical systems [216] and availability of LNG carrier propulsion [217] provide the modelling basis. FLNG profitability, reliability and condition-based monitoring have been reviewed [218], and condition-based maintenance systems for LNG FPSOs developed [219]. Simulation of repairable deteriorating systems [220] and integrity management with emphasis on design for structural damage [221] connect availability to maintenance and integrity.

A body of applied work on maintenance, integrity and supply in the oil and gas sector complements these models. Risk-based inspection for fitness-for-service of ageing pressure vessels [222], condition-based maintenance of CALM buoy bearings and swivels [223], integrity assurance of FSO turret mooring systems [224], reliability and integrity management of fired equipment [225], non-intrusive inspection of pressure vessels [226] and predictive maintenance and condition monitoring in energy infrastructure [227] address equipment integrity. Reviews of NDT-based integrity management and corrosion risk assessment for refinery process equipment [228], of non-destructive testing for weld integrity in high-capacity power infrastructure [229] and of non-destructive testing for predictive failure analysis in mechanical systems [230] show how inspection data feed the failure rates used in availability models. Reliability engineering and failure analysis in complex systems [231], risk-based process engineering for natural gas infrastructure [232], interpretable machine learning for early failure prediction [233] and machine learning and data-driven methods for industrial automation and process control [234] illustrate the move toward data-driven maintenance. Strategic procurement and inventory availability for plant uptime [235, 236], supply chain risk management for gas processing projects [237], maintenance-driven materials readiness [238], supply chain resilience for critical infrastructure and gas processing plants [239], reservoir forecasting [240] and UAV-based corridor monitoring [241] show how logistics and production forecasting support availability.

2.7. Human and Organizational Factors in Operational Safety

Human and organizational factors influence both the frequency and the consequences of FPSO accidents. Dynamic Bayesian models of human factors in blowouts [242], human factors in emergency response management [243], quantitative risk analysis of fire and explosion incorporating human and organizational factors [244], virtual experimental data collection for human reliability [245], critical analysis of human reliability in process operation [246] and Bayesian human reliability analysis of tanker operations [247] show how human performance can be represented. Dynamic occupational risk models for harsh environments [248], risk-based cost benefit analysis of offshore resource centres [249] and operational risk assessment for marine vessels [250] extend this to remote and harsh settings.

Applied studies of safety management describe the organizational barriers that support design safety in operation. Operational integrity in high-risk drilling [251], data-driven occupational safety risk control in energy infrastructure [252], near-miss and hazard observation data [253], contractor safety governance [254], organizational learning maturity models [255], proactive hazard recognition and near-miss reporting [256], incident prevention in maintenance engineering [257], and institutionalizing life-preserving practices [258] represent this literature. Analyses of leak verification as an operational barrier on the Norwegian shelf [154] and of human reliability in process operation [246] address the maintenance and control room interfaces that often determine whether a release occurs and whether it becomes an escalated event.

2.8. Research Gap

Three gaps emerge from the review. First, optimization research has concentrated on mooring, riser and hull subsystems with structural or cost objectives, while personnel risk and production availability have rarely been included as explicit objectives [6, 25, 32]. Second, risk assessment and layout studies quantify the safety effect of separation, congestion and blast walls for given designs [50, 51, 111, 142], but they do not trade these measures against each other or against cost and availability. Third, availability studies treat equipment redundancy and offloading separately from safety [18, 19], even though compression configuration affects both leak frequency and availability, and mooring concept affects both motions and collision risk [7, 15]. This study addresses these gaps by optimizing safety, availability and cost simultaneously over layout, equipment, storage and mooring variables, and by testing how the preferred design responds to uncertainty and to the environment [32, 158].

3. Methodology

This section sets out the optimization framework, the reference facility, the safety, production and cost models, the optimization algorithm and the procedures used to select designs and test their robustness. The approach follows the logic of simulation-based design optimization used in mooring and riser design, in which a parametric model of the system is coupled with an evolutionary search [25, 73, 74], but it extends the objective set from structural or cost measures to personnel risk and production availability, which are evaluated using simplified forms of the QRA and availability models reviewed in Section 2 [19, 20, 34]. All model inputs are representative values chosen within ranges reported in the cited literature for the reference facility defined here; they are not measurements from any operating unit, and the framework is intended to be re-parameterized with project data [156, 158].

3.1. Framework Overview

The framework, shown in Figure 1, links six design variables to three objectives through three coupled models. The safety model estimates PLL from hydrocarbon release frequency, ignition, congestion-driven explosion overpressure, escalation through the blast wall, impact on the accommodation and offloading and collision risk [14, 15, 135]. The production model estimates availability from compression redundancy, motion-induced process upsets, a stochastic simulation of offloading deferral and the outage that follows escalated events [18, 123, 174]. The cost model estimates capital expenditure from deck and hull length, storage volume, compression trains, mooring concept and blast wall rating [6, 31, 114]. The NSGA-II algorithm searches for the Pareto front [73, 74], TOPSIS selects preferred designs under alternative preferences, and Monte Carlo simulation, tornado analysis and a harsh-environment case test the robustness of the selection [158, 248].

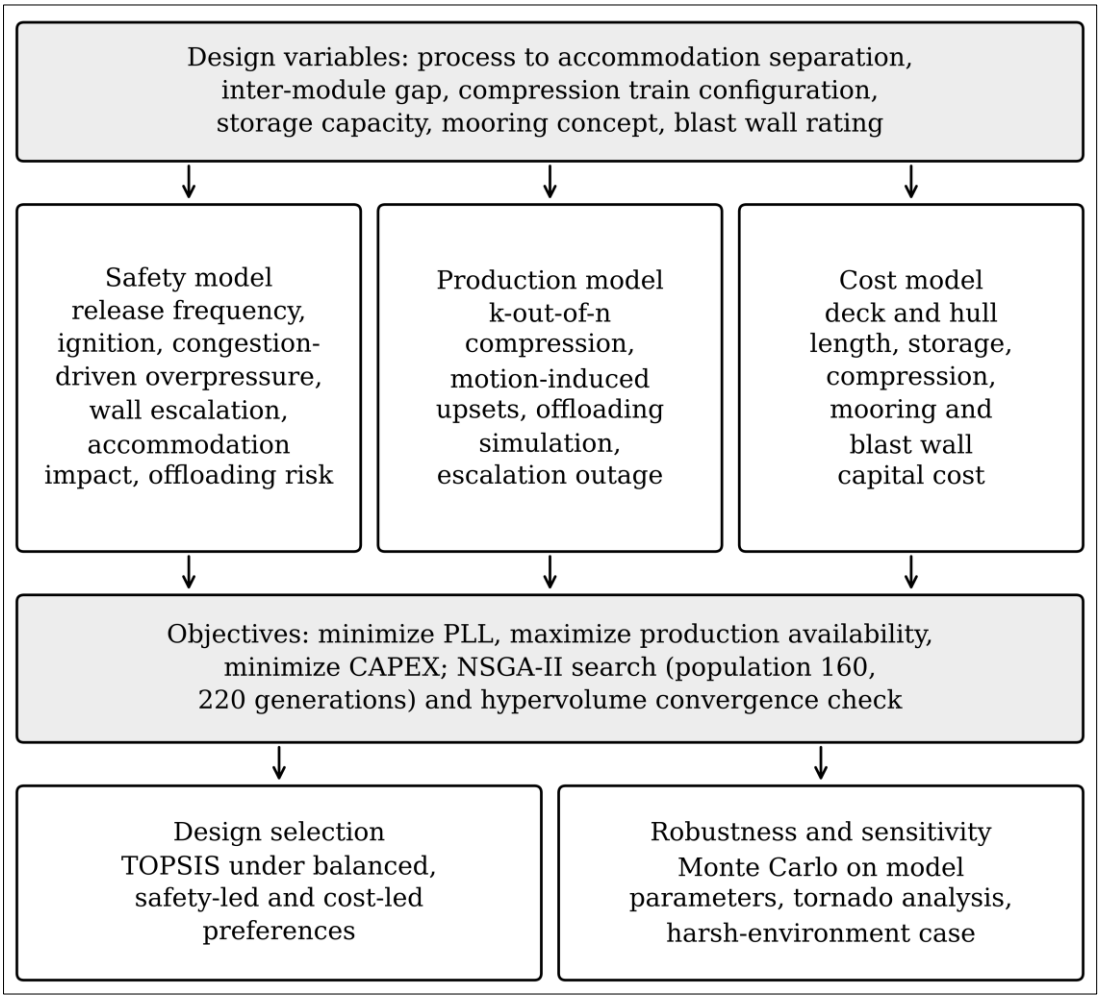


Fig 1: Framework for multi-objective FPSO design optimization linking six design variables to personnel risk, production availability and capital cost.

3.2. Reference Facility and Design Variables

The reference facility is a ship-shaped FPSO with a plateau rate of 150,000 barrels per day, a process and utility topsides of the type described in FPSO design guidance [3, 4], 14 personnel normally present in process areas and 70 in the accommodation. Table 1 defines the six design variables, their bounds and the values of a conventional reference design used for comparison. The separation distance between the process area and the accommodation and the gap between process modules are the principal layout levers identified in FPSO and FLNG layout studies [50, 108, 111, 142]. The compression configuration represents the redundancy decision for the most failure-prone rotating equipment [18, 213]. Storage capacity governs the buffer between production and

offloading [5, 174]. The mooring concept distinguishes spread mooring, common in benign West African waters, from an internal turret that allows the vessel to weathervane [7, 55, 106]. The blast wall rating represents the design overpressure of the wall separating process from utility and accommodation areas [13, 143, 144].

Table 1: Design variables, bounds and reference design values.

Variable	Symbol	Lower bound	Upper bound	Reference design
Process to accommodation separation (m)	d	40	150	55
Inter-module gap (m)	g	1.0	6.0	1.5
Compression trains (2, 3 or 4)	n_c	2	4	3
Storage capacity (million bbl)	S	1.0	2.2	1.6
Mooring concept (0 spread, 1 internal turret)	t	0	1	0
Blast wall rating (bar)	w	0.5	2.0	1.0

3.3. Safety Model

The annual frequency of significant hydrocarbon releases increases with the number of compression trains, which are the dominant contributors to process leaks [152, 153, 156]:

$$\lambda = \lambda_0 + \lambda_c \, n_c \tag{1}$$

with $\lambda_0 = 0.22$ and $\lambda_c = 0.035$ per year. The ignition probability of a significant release is $p_{\mathrm{ign}} = 0.06$ [149, 156]. Peak explosion overpressure in the process module decreases with inter-module gap because wider gaps reduce congestion and confinement, as shown by dispersion and explosion studies of safety gaps [50, 112, 142]:

$$P = P_0 \exp[-k(g - 1)] \tag{2}$$

with $P_0 = 2.6$ bar and $k = 0.28$ per metre. Escalation through the blast wall follows a logistic fragility function of the margin between overpressure and wall rating [13, 136, 145]:

$$p_{\mathrm{esc}} = \frac{1}{1+\exp[-(P-w)/\sigma]} \tag{3}$$

with $\sigma = 0.18$ bar. Overpressure at the accommodation decays with separation distance as $P_{\mathrm{LQ}} = P(r_0/d)^2$ with $r_0 = 15$ m, and the fatality probability for accommodation occupants combines blast and escalated fire contributions [133, 134, 148]:

$$p_{f,\mathrm{LQ}} = \frac{0.3}{1+\exp[-(P_{\mathrm{LQ}}-0.35)/0.07]} + 0.05\, p_{\mathrm{esc}} \left(\frac{40}{d}\right)^2 \tag{4}$$

The fatality probability in the process area increases with overpressure as $p_{f,p} = 0.08 + 0.25\, P/P_0$ [12, 135]. The potential loss of life is then

$$\mathrm{PLL} = \lambda \, p_{\mathrm{ign}} \left(N_p \, e_p \, p_{f,p} + N_{\mathrm{LQ}} \, e_{\mathrm{LQ}} \, p_{f,\mathrm{LQ}}\right) + \mathrm{PLL}_{\mathrm{off}} + N_{\mathrm{LQ}} \, \mu \tag{5}$$

with $N_p = 14$, $e_p = 0.6$, $N_{\mathrm{LQ}} = 70$ and $e_{\mathrm{LQ}} = 0.8$. The offloading and collision term $\mathrm{PLL}_{\mathrm{off}}$ is 2.2×10^{-3} per year for spread mooring and 1.4×10^{-3} for a turret, reflecting reduced relative motion and contact probability with a weathervaning vessel [15, 175, 176]. The non-process term $\mu = 1.6 \times 10^{-4}$ per person-year represents occupational and transport risk [34, 248].

3.4. Production Availability Model

Production availability is the product of compression capacity availability, motion-related upsets, offloading deferral, planned shutdown and outage after escalated events [18–20]:

$$A = C_c (1 - m_t)(1 - \delta_{\mathrm{off}})\left(1 - \delta_{\mathrm{pl}}\right)(1 - \delta_{\mathrm{esc}}) \tag{6}$$

The compression term is the expected capacity of n_c identical trains, each of capacity $c = 1/n_c$ for three or four trains and $c = 1$ for two fully rated trains, with unit availability $A_u = \mathrm{MTBF}/(\mathrm{MTBF} + \mathrm{MTTR})$ for an MTBF of 2,600 h and MTTR of 60 h [211, 214, 215]. The MTTR assumes that critical spares are held on board or in a responsive supply chain, consistent with inventory availability and supply chain resilience practice for gas processing plants [236, 239]:

$$C_c = \sum_{k=0}^{n_c} \binom{n_c}{k} A_u^k (1 - A_u)^{n_c - k} \min(1,\, k\, c) \tag{7}$$

The motion-related deferral m_t is 2.4 percent for spread mooring and 0.8 percent for a turret, representing loss of separation and treating efficiency and process trips under roll and pitch [123, 126, 127]. Planned shutdown is $\delta_{\mathrm{pl}} = 0.015$. The escalation outage is $\delta_{\mathrm{esc}} = \lambda \, p_{\mathrm{ign}} \, p_{\mathrm{esc}} \, \tau$ with an outage duration $\tau = 0.25$ year [8, 221].

Offloading deferral was estimated by stochastic simulation. Shuttle tankers are called when cargo reaches half of storage capacity, and the time to the next completed offloading is the sum of a gamma-distributed interarrival time with shape 8 and a weather waiting time that is exponentially distributed with mean 1.1 days for spread mooring and 0.6 days for a turret, reflecting the greater weather sensitivity of tandem offloading from a fixed-heading vessel [174, 175, 189]. Production is deferred whenever the arrival time exceeds 95 percent of the time to fill the tanks:

$$\delta_{\mathrm{off}} = \frac{\sum_j \max(0,\, T_j - 0.95\, S/Q)}{\sum_j T_j} \tag{8}$$

where T_j is the arrival time in cycle j and Q is the production rate. The simulation uses 400 replications of 60 cycles with common random numbers for all designs, so that differences between designs are not caused by sampling noise [20, 211].

3.5. Cost Model

Capital expenditure is estimated from deck and hull dimensions and from equipment and mooring choices [31, 113, 114]. The deck length required to accommodate the process, separation and module gaps is $L_d = 150 + 0.9(d - 40) + 18\,g$ metres, and the hull length is the larger of the length needed for storage and that needed for the deck:

$$L_h = \max(240,\ 180 + 55\,S,\ L_d + 60) \tag{9}$$

The Capital Cost in USD Million Is

$$\mathrm{CAPEX} = 900 + 4.6\,L_h + 120\,S + C_{\mathrm{comp}}(n_c) + C_{\mathrm{moor}}(t) + 55\,w \tag{10}$$

with compression costs of 310, 360 and 420 for two, three and four trains, and mooring costs of 140 for spread mooring and 420 for an internal turret [6, 106]. The coefficients produce capital costs between about USD 2.6 and 3.9 billion over the design space, which is consistent in order of magnitude with large new-build FPSOs [2, 4].

3.6. Optimization Algorithm

The problem was solved with the NSGA-II algorithm, which has been applied to mooring and floating system design [73, 74], implemented in the pymoo library. Table 2 lists the settings. The integer variables (compression trains and mooring concept) were treated as continuous during search and rounded during evaluation, and the final front was filtered for non-dominance after rounding. Convergence was monitored by the hypervolume indicator relative to a reference point of PLL 0.40 per year, availability 0.85 and CAPEX USD 4,200 million [32, 76]. A fixed random seed was used for reproducibility, and the full search required 35,200 design evaluations, each taking a fraction of a second, so the framework can be rerun quickly as design assumptions change during FEED.

Table 2: NSGA-II settings.

Setting	Value
Population size	160
Generations	220
Crossover	Simulated binary crossover, probability 0.9, distribution index 15
Mutation	Polynomial mutation, distribution index 20
Duplicate elimination	Enabled
Integer variables	Rounded at evaluation
Hypervolume reference point	PLL 0.40 per year; availability 0.85; CAPEX USD 4,200 million

3.7. Design Selection, Robustness and Sensitivity

Preferred designs were selected from the Pareto front by TOPSIS using unavailability $1 - A$ in place of availability so that all criteria are minimized and relative differences in production loss are preserved [151, 169]. Three weight sets were used: balanced (PLL 0.4, unavailability 0.3, CAPEX 0.3), safety-led (0.6, 0.2, 0.2) and cost-led (0.2, 0.3, 0.5). The lowest-risk design that weakly dominates the reference design on all three objectives was also identified. Robustness was tested by evaluating the reference design and the selected designs over 3,000 Monte Carlo samples in which release frequency, ignition probability, overpressure, fatality probability and offloading risk were multiplied by lognormal factors with error factors of 3, 2, 1.5, 1.5 and 2, and capital cost by a triangular factor between 0.9 and 1.3 [135, 156, 158]. A one-at-a-time tornado analysis was performed on the balanced design, and single-variable sweeps were computed about it. Finally, a harsh-environment case increased motion-related deferral to 6.0 percent for spread mooring and 1.2 percent for a turret and mean weather waiting to 3.0 and 1.0 days, and the optimization was repeated [54, 82, 248].

4. Results

This section reports the convergence of the optimization and the shape of the Pareto front, the design variable patterns that characterize efficient designs, the selected designs and their comparison with the reference design, the effect of individual variables, the robustness of the selected designs to parameter uncertainty and the sensitivity of the results to model parameters and to a harsh environment. Results are reported for the reference environment unless stated otherwise. As in other multi-objective studies of floating systems, the front is interpreted as a set of trade-off options rather than as a single optimum, and the selection of a design depends on stakeholder preferences that are made explicit through the TOPSIS weights [73, 74, 76].

4.1. Convergence and Pareto Front

The hypervolume rose from 59.33 in the first generation to 65.07 after 220 generations, and 99 percent of the total improvement was achieved by generation 39, indicating that the search converged well within the generation budget (Figure 3). The final front contains 160 non-dominated designs spanning PLL from 0.035 to 0.272 per year, availability from 0.926 to 0.972 and CAPEX from USD 2,602 million to 3,922 million (Figure 2). The front shows a steep initial reduction of PLL as CAPEX rises from the minimum, followed by a long flat region beyond about USD 3,400 million in which additional expenditure buys little further risk reduction, a pattern consistent with the diminishing returns reported in layout and blast mitigation studies [50, 51, 138].

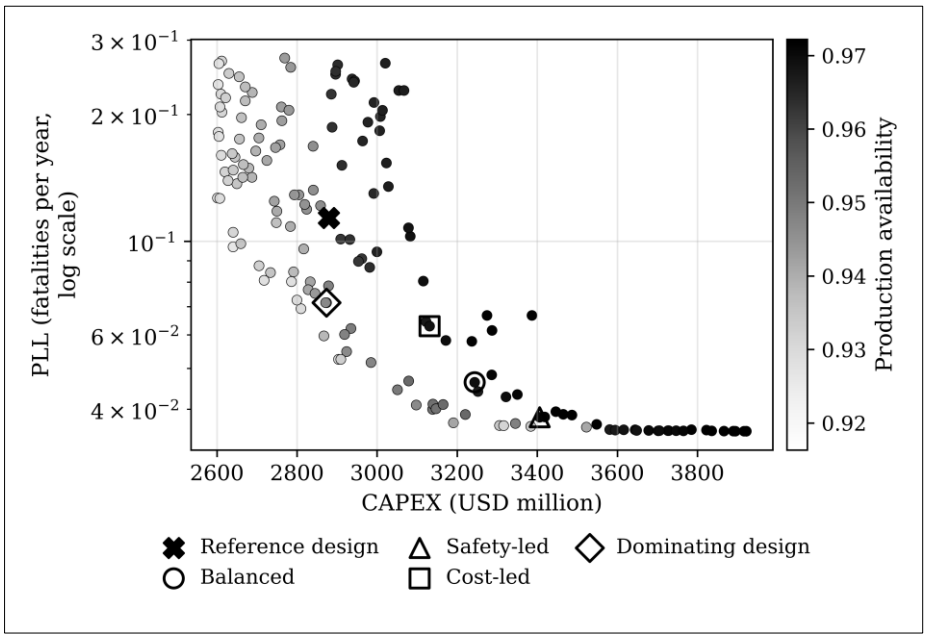


Fig 2: Pareto front of potential loss of life against capital cost, shaded by production availability, with the reference design and selected designs marked.

The reference design, with PLL 0.114 per year, availability 0.944 and CAPEX USD 2,880 million, lies well inside the front. Many front designs improve on it in all three objectives, and the lowest-risk of these, labelled the dominating design in Figure 2, reduces PLL to 0.072 per year while slightly raising availability and lowering CAPEX. The reference design is therefore inefficient: its parameters were chosen to represent common practice rather than an optimized arrangement, and the result shows that the gains from joint optimization are available without any cost penalty [4, 10].

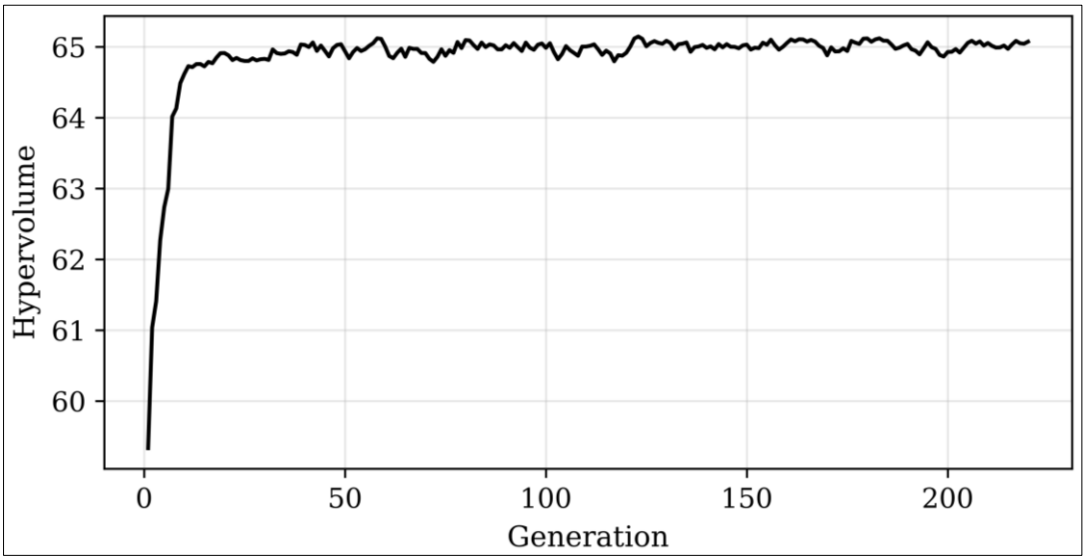


Fig 3: Convergence of the NSGA-II search measured by the hypervolume of the non-dominated set in each generation.

4.2. Design Variable Patterns on the Front

Figure 4 shows the normalized design variables of all front designs, and Table 3 summarizes their distribution. All 160 front designs use two fully rated compression trains. This configuration has fewer leak sources than three or four smaller trains, and with the unit reliability assumed its expected capacity of 0.9995 exceeds that of three 50 percent trains, so it dominates on safety, availability and cost simultaneously [18, 152, 213]. Separation distance clusters at the lower end of its range, with a mean of 61 m against a range of 40 to 150 m, because separation increases deck and hull length and is a less efficient risk control than congestion and wall rating. Inter-module gap and blast wall rating span their full ranges and drive movement along the front. Storage capacity has a mean of 1.40 million barrels, and 44 percent of front designs use a turret.

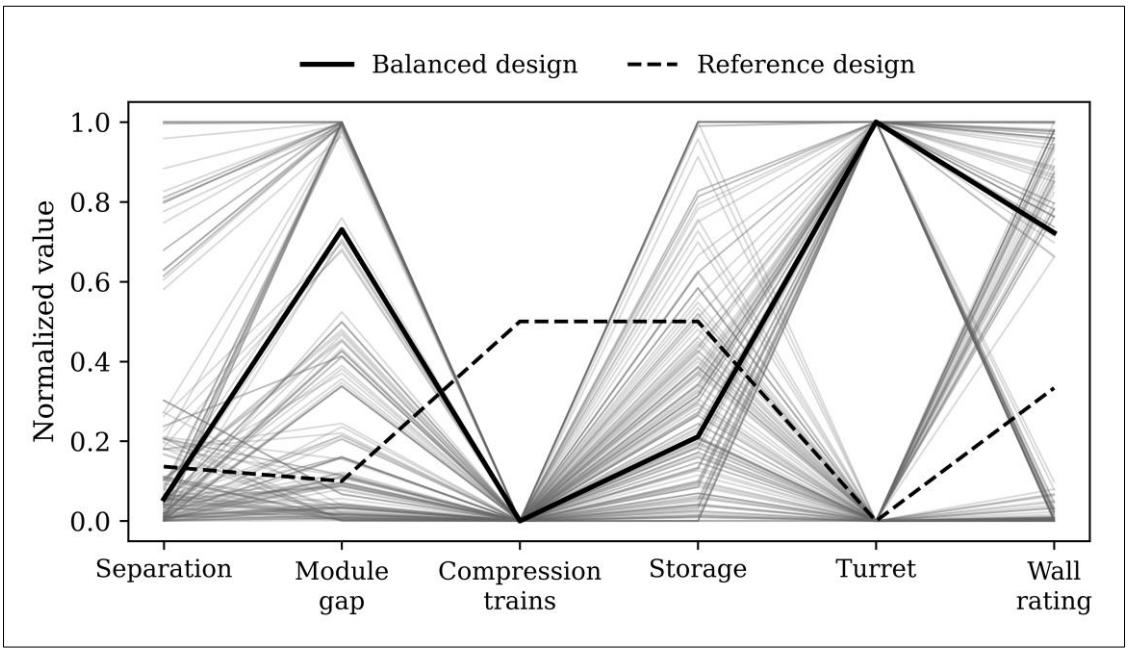


Fig 4: Normalized design variables of the 160 Pareto-optimal designs (grey), the balanced design (solid) and the reference design (dashed).

Table 3: Distribution of design variables across the Pareto front.

Variable	Minimum	Mean	Maximum
Separation (m)	40.0	60.5	150.0
Inter-module gap (m)	1.0	3.0	6.0
Compression trains	2	2.0	2
Storage capacity (million bbl)	1.00	1.40	2.20
Turret share	0	0.44	1
Blast wall rating (bar)	0.50	1.13	2.00

4.3. Selected Designs and Comparison with the Reference Design

Table 4 lists the selected designs. The balanced design combines a separation of 46 m, a module gap of 4.7 m, two fully rated compression trains, storage of 1.25 million barrels, an internal turret and a blast wall rated at 1.58 bar. Relative to the reference design it reduces PLL by 59 percent, from 0.114 to 0.046 per year, raises availability by 2.5 percentage points, from 0.944 to 0.969, and increases CAPEX by USD 364 million or 12.6 percent. The safety-led design widens the module gap to 5.9 m and raises the wall rating to 1.97 bar, reducing PLL to 0.038 per year at a CAPEX of USD 3,406 million. The cost-led design retains a narrower gap of 2.9 m and achieves PLL of 0.063 per year at USD 3,131 million. All three preference-based selections use a turret, which delivers the highest availability, while the dominating design retains spread mooring and achieves its gains through layout and equipment alone.

Table 4: Selected designs and the reference design.

Design	d (m)	g (m)	n_c	S (million bbl)	Mooring	w (bar)	PLL (per year)	Availability	CAPEX (USD million)
Reference	55.0	1.50	3	1.60	Spread	1.00	0.1136	0.9439	2880
Balanced	46.1	4.65	2	1.25	Turret	1.58	0.0463	0.9693	3244
Safety-led	49.4	5.88	2	1.46	Turret	1.97	0.0383	0.9706	3406
Cost-led	52.0	2.85	2	1.24	Turret	1.83	0.0629	0.9686	3131
Dominating	42.1	3.13	2	1.51	Spread	1.97	0.0715	0.9473	2874

Table 5 decomposes PLL and the main intermediate quantities. In the reference design the module overpressure of 2.26 bar exceeds the 1.0 bar wall rating so that escalation is almost certain, and accommodation risk, at 0.052 per year, is the largest contributor. In the balanced design the wider gap lowers overpressure to 0.94 bar, below the 1.58 bar wall rating, and escalation probability falls to 0.027. Accommodation risk falls by 83 percent to 0.009 per year and process-area risk by 49 percent, and non-process risk of 0.011 per year becomes the second largest contributor. The turret reduces motion-related deferral from 2.4 to 0.8 percent and offloading deferral from 1.26 to 0.74 percent, and these two effects together account for most of the availability gain [7, 126, 174].

Table 5: Risk and production breakdown for the reference and balanced designs.

Quantity	Reference design	Balanced design
Module overpressure (bar)	2.26	0.94
Escalation probability	0.999	0.027
Overpressure at accommodation (bar)	0.168	0.099
Process-area PLL (per year)	0.0487	0.0248
Accommodation PLL (per year)	0.0515	0.0089
Offloading and collision PLL (per year)	0.0022	0.0014
Non-process PLL (per year)	0.0112	0.0112
Compression capacity availability	0.9992	0.9995
Motion-related deferral	0.024	0.008
Offloading deferral	0.0126	0.0074
Hull length (m)	268	299

4.4. Effects of Individual Design Variables

Figure 5 shows the effect of varying separation, module gap, storage and wall rating one at a time about the balanced design. Module gap has the largest effect on risk: increasing it from 1 m to 6 m reduces PLL from 0.173 to 0.039 per year while CAPEX rises from USD 3,013 million to 3,355 million. Raising the wall rating from 0.5 to 2.0 bar reduces PLL from 0.079 to 0.045 per year for an increase of only USD 83 million, the cheapest risk reduction in the design space, but its benefit saturates once the rating exceeds the module overpressure. Increasing separation from 40 to 150 m reduces PLL only from 0.051 to 0.040 per year while adding USD 455 million, because once escalation is prevented the accommodation is already well protected. Storage capacity has no effect on risk in the model but raises availability from 0.967 to 0.972 across its range, at a cost of USD 152 million. These results are consistent with the emphasis in FLNG and FPSO layout studies on reducing congestion and on blast wall design rather than on separation alone [50, 51, 111, 142].

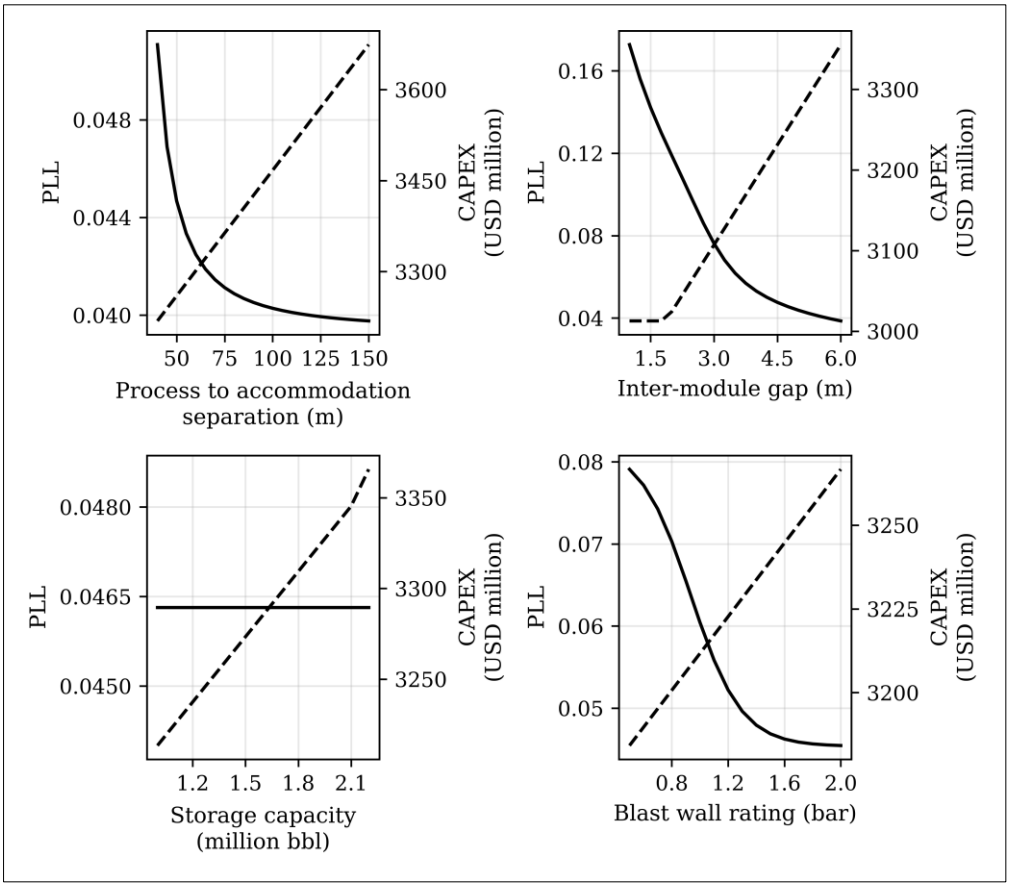


Fig 5: Effect of single design variables on potential loss of life (solid) and capital cost (dashed) about the balanced design.

4.5. Robustness to Parameter Uncertainty

Table 6 and Figure 6 report the results of 3,000 Monte Carlo samples of the uncertain parameters. The median PLL of the reference design is 0.122 per year with a 90 percent interval from 0.039 to 0.463, reflecting the wide uncertainty in release frequency and ignition probability [152, 156]. The balanced design has a median of 0.049 per year with an interval from 0.022 to 0.166, and its PLL is lower than that of the reference design in all 3,000 samples, as are those of the other selected designs. The ordering of designs is therefore robust to parameter uncertainty even though absolute values are not. The capital cost distributions are shifted upward relative to the deterministic values because of the right-skewed cost multiplier, with the balanced design at a median of USD 3,418 million.

Table 6: Robustness of selected designs over 3,000 Monte Carlo samples (median with 5th and 95th percentiles).

Design	PLL (per year)	Mean availability	CAPEX (USD million)	Share of samples with PLL below reference
Reference	0.122 (0.039 to 0.463)	0.942	3035 (2724 to 3516)	n/a
Balanced	0.049 (0.022 to 0.166)	0.969	3418 (3069 to 3961)	1.00
Safety-led	0.039 (0.019 to 0.119)	0.971	3589 (3222 to 4159)	1.00
Cost-led	0.068 (0.025 to 0.258)	0.968	3300 (2962 to 3823)	1.00
Dominating	0.078 (0.028 to 0.326)	0.947	3029 (2719 to 3509)	1.00

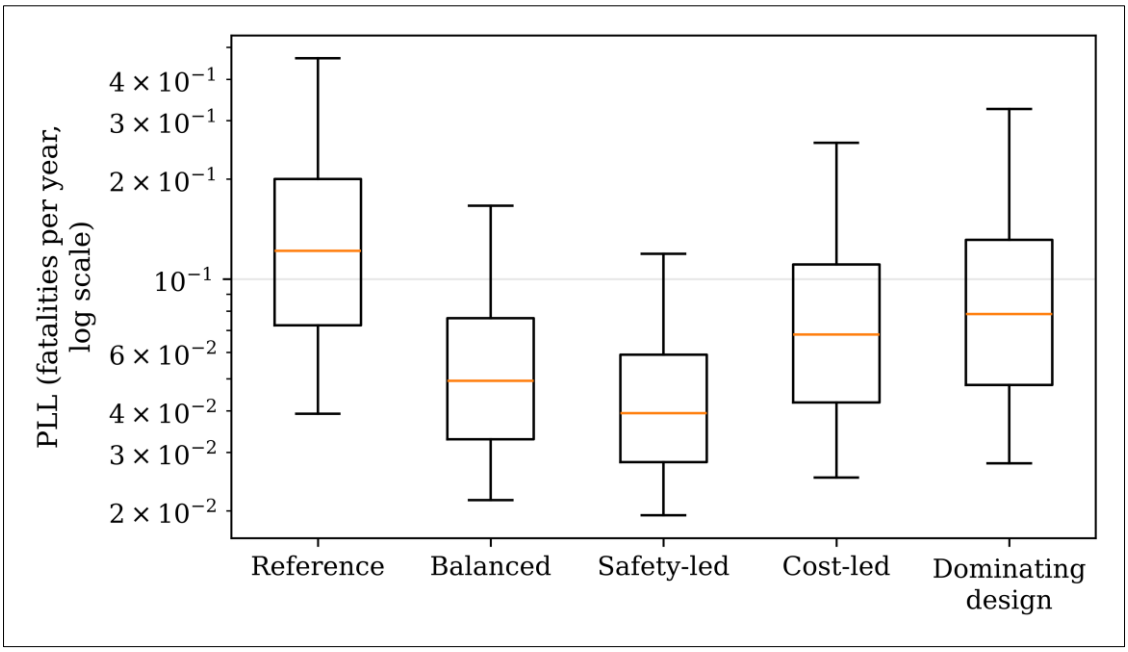


Fig 6: Distributions of potential loss of life for the reference and selected designs over 3,000 Monte Carlo samples. Boxes show the interquartile range and whiskers the 5th and 95th percentiles.

4.6. Sensitivity Analysis and Harsh Environment

The tornado diagram in Figure 7 shows that release frequency is the dominant parameter for the balanced design, with PLL ranging from 0.024 to 0.114 per year over a factor of three either way, followed by ignition probability (0.030 to 0.080), overpressure (0.038 to 0.070) and fatality probability (0.035 to 0.063). Offloading risk has a negligible effect. Because release frequency and ignition probability scale all hydrocarbon risk terms, they affect absolute risk but not the ranking of layout options, whereas overpressure uncertainty directly affects the margin to the wall rating and therefore the value of the wall [135, 139, 145].

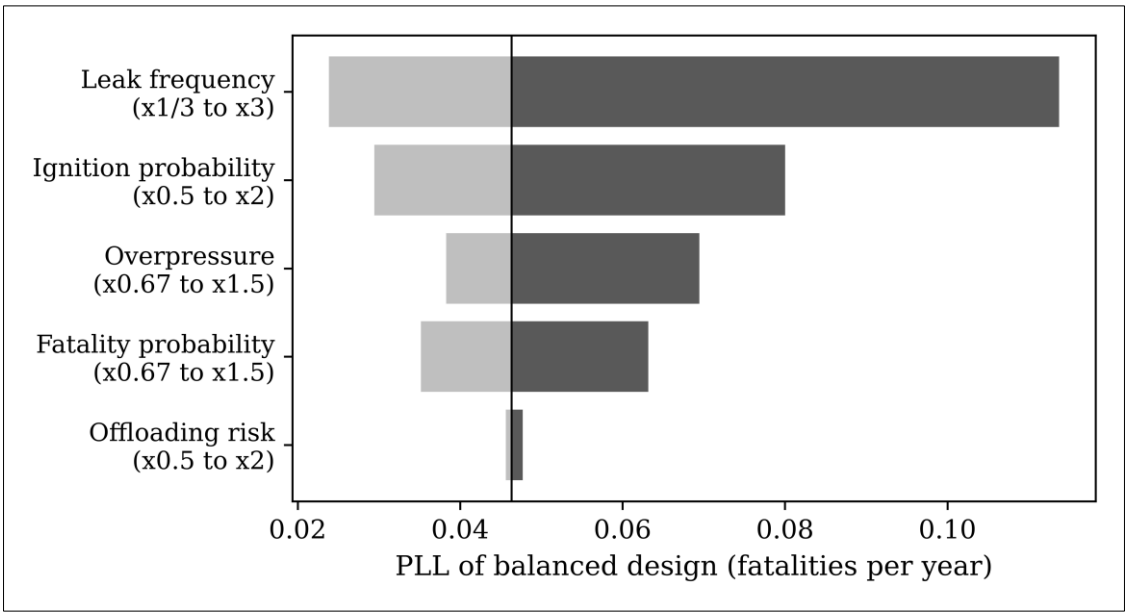


Fig 7: Tornado diagram of potential loss of life for the balanced design. Dark bars show the high value and light bars the low value of each parameter.

Table 7 compares the reference and harsh environments. In the harsh environment, the reference design with spread mooring loses availability to 0.837 because of motion-related upsets and offloading delays, while the same design with a turret retains 0.957. The balanced design selected in the harsh environment uses a turret, a separation of 43 m, a module gap of 5.3 m, storage of 1.19 million barrels and a wall rating of 1.96 bar, and it achieves PLL of 0.043 per year, availability of 0.955 and CAPEX of USD 3,298 million. At its storage capacity, offloading deferral would be 14.7 percent with spread mooring but only 1.8 percent with a turret. The range of availability on the harsh-environment front widens to 0.747 to 0.966. These results show that the mooring decision, which is a modest availability lever in benign conditions, becomes decisive in harsh conditions, which agrees with industry practice of turret mooring in the North Sea and other harsh regions [54, 82, 105].

Table 7: Comparison of reference and harsh environments.

Quantity	Reference environment	Harsh environment
Reference design availability, spread mooring	0.944	0.837
Reference design availability, turret	0.966	0.957
Balanced design PLL (per year)	0.046	0.043
Balanced design availability	0.969	0.955
Balanced design CAPEX (USD million)	3244	3298
Balanced design mooring	Turret	Turret
Availability range on Pareto front	0.926 to 0.972	0.747 to 0.966

5. Discussion

This section interprets the results for FPSO concept design practice, examines the trade-offs between safety, reliability and cost that the front reveals, compares the findings with previous studies and sets out the limitations of the study and directions for further work. The discussion emphasizes the mechanisms that produce the results, because the value of a parametric optimization at concept stage lies less in the specific numbers, which depend on representative inputs, than in identifying which design levers matter and under what conditions their ranking changes [32, 34, 158]. Where the results depend on particular assumptions, such as the reliability of compression trains or the environmental conditions at the site, the discussion indicates how project-specific data would alter the conclusions [20, 82].

5.1. Implications for FPSO Concept Design

Four implications follow from the results. First, congestion control through inter-module gaps and blast wall rating should be prioritized over separation distance as the primary risk-reduction lever. The results show that keeping module overpressure below the wall rating prevents escalation and protects the accommodation more cheaply than moving it further away, which supports the inherent safety principle of reducing hazard at source and agrees with layout studies of safety gaps and blast walls [13, 50, 51, 111]. Second, the wall rating should be chosen jointly with the module gap, because the wall is cost-effective only when its rating exceeds the expected overpressure. Treating the two separately risks either an inadequate wall or an over-designed one [143–145].

Third, compression redundancy should be evaluated for its effect on leak frequency as well as on availability. Under the reliability data assumed, two fully rated trains dominate three or four smaller ones on all three objectives, but this result depends on high unit availability. Where compressor reliability is lower, or where partial throughput is valuable, more trains may be preferred, and condition monitoring based on non-destructive testing and predictive failure analysis can raise unit availability enough to change the ranking [227, 230]; the framework allows this trade-off to be tested with project data [18, 153, 213]. Fourth, the mooring concept should be selected with explicit regard to environment and offloading. In the reference environment a turret offered a moderate availability gain at a capital cost of about USD 280 million, while in the harsh environment it prevented the loss of more than 10 percentage points of availability [7, 106, 174].

5.2. Safety, Reliability and Cost Trade-Offs

The front shows that the trade-off between safety and cost is steep at low expenditure and flat at high expenditure. Most of the attainable risk reduction is achieved by USD 3,200 million to 3,400 million, and designs beyond this point buy little additional safety. The balanced and safety-led designs lie near the knee of the front, which is where most decision makers would be expected to choose when risk reduction is valued but not without limit [34, 159]. The trade-off between safety and availability is weak: the safety-led design has the highest availability of the selected designs, because the same turret and storage decisions that reduce offloading risk also reduce deferral. This finding contradicts the common perception that safety and production compete at the concept stage, at least for the mechanisms represented here [10, 18].

The trade-off between availability and cost is driven mainly by mooring and storage. Storage capacity improves availability by reducing offloading deferral but has no safety benefit in the model, so its value depends on the price of oil and the cost of hull volume [5]. The finding that the reference design is dominated by designs of equal or lower cost shows that the largest gains from optimization come not from spending more but from rearranging the same budget: wider gaps and a stronger wall paid for by shorter separation and fewer compression trains [29, 30, 109].

5.3. Comparison with Previous Studies

The predominance of congestion and wall rating over separation is consistent with the findings of Li and colleagues that safety gaps reduce gas dispersion and explosion consequences on FLNG vessels and that blast wall layout can be optimized for mitigation [50, 51, 142], and with Baalisampang and colleagues' finding that equipment congestion controls LNG release consequences [111, 112]. The importance of release frequency in the sensitivity analysis agrees with analyses of hydrocarbon leaks on the Norwegian shelf, which show that leak frequency varies widely between installations and is strongly influenced by maintenance practice [152, 154, 155]. The availability effect of mooring concept is consistent with studies of motion effects on separation and distillation [123, 126, 127] and with offloading operability studies [174, 189, 194].

Previous optimization studies have focused on mooring, riser and hull subsystems with structural and cost objectives [6, 23, 27, 73]. The present study complements them by optimizing at the facility level with safety and availability as objectives, and its results suggest that subsystem optimizations should be nested within a facility-level search, because decisions such as mooring concept or hull length that are taken as fixed in subsystem studies have large effects on facility-level risk and availability [25, 92]. Studies of leak verification as an operational barrier [154] and of human reliability in process operation [246] indicate that operational controls can further reduce release and ignition frequencies, which the sensitivity analysis shows to be the dominant parameters.

5.4. Limitations and Future Work

The study has several limitations. The safety model uses parametric relationships for overpressure, escalation and fatality rather than computational fluid dynamics and structural analysis, and it represents the accommodation impact through a single distance-decay function [135, 136, 147]. The availability model uses steady-state approximations and does not represent maintenance resource constraints, spare parts logistics or weather windows for repair [20, 214, 220]. The cost model represents hull and deck sizing through linear relationships and omits schedule and operating cost [31, 114]. The representative parameter values were chosen within ranges in the literature but are not calibrated to a specific project, so absolute results should not be used for design without project-specific data [156, 158].

Future work should address these limitations in three ways. The first is to replace the parametric explosion model with a surrogate trained on computational fluid dynamics simulations, following the use of surrogate models in mooring and riser optimization [74, 75, 101] and of CFD-driven design for separation equipment [129], so that overpressure is predicted from actual module geometry. The second is to couple the facility-level optimization with mooring and riser optimization so that hull dimensions, offsets and riser configurations are jointly determined [25, 92, 103]. The third is to extend the framework into operation by updating release frequencies and equipment reliability from operating data, using machine learning methods for process monitoring and failure prediction [233, 234] and dynamic Bayesian availability assessment [216], so that the design basis is revisited as operating data accumulate.

6. Conclusion

This study formulated FPSO concept design as a three-objective optimization of potential loss of life, production availability and capital cost over six design variables, and solved it with NSGA-II using coupled safety, production and cost models. The resulting Pareto front of 160 designs showed that a conventional reference design was dominated by designs of equal or lower cost, and that a balanced design reduced potential loss of life by 59 percent and raised production availability by 2.5 percentage points for a 12.6 percent increase in capital cost. The ordering of designs was robust to parameter uncertainty, with all selected designs outperforming the reference design in every Monte Carlo sample.

The results identify the levers that matter most at concept stage. Inter-module gap and blast wall rating controlled risk far more efficiently than separation distance, because keeping module overpressure below the wall rating prevents escalation that would otherwise dominate accommodation risk. Two fully rated compression trains dominated larger numbers of smaller trains under the assumed reliability, and a turret-moored concept was selected under all preferences in the reference environment and became decisive in a harsh environment, where it preserved more than 10 percentage points of availability.

For practitioners, the framework provides a transparent and reproducible way to explore FPSO design trade-offs before detailed engineering, and to identify designs that improve safety and production reliability together. Its parametric structure allows project-specific data, higher-fidelity explosion and availability models and coupled mooring and riser optimization to be incorporated as the design matures.

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