



Views & Comments

Future Perspectives of Large-Scale Floating Transshipment Terminals

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1. Introduction

Container shipping has transformed global trade since the maiden voyage of the SS Ideal X in 1956, which is a converted World War II T-2 oil tanker. The adoption of standardized shipping units, such as the twenty-foot equivalent unit (TEU) and forty-foot equivalent unit, has significantly enhanced logistics efficiency. Currently, more than 6000 fully cellular container ships are in operation, with a combined capacity of approximately 30 million TEUs. Significant changes have been incorporated over time, resulting in substantial advancements in global trade and logistics, and enhancing shipping efficiency.

The trend toward larger container ships, known as ultra-large container vessels (ULCVs), is driven by economies of scale. These vessels are at least 35% more energy efficient than medium-sized container ships, offering significant environmental benefits, particularly in terms of reducing carbon emissions. However, the rise of ULCVs, with some exceeding a capacity of 24 000 TEUs, has introduced new challenges, particularly for port infrastructure [1]. Significant development in port infrastructure is crucial for the advancement of ULCVs, which are expected to exceed a capacity of 30 000 TEU in the future.

Although ULCVs reduce per-unit transportation costs and carbon emissions, their large drafts (often exceeding 16–17 m [2,3]) prevent them from accessing many ports. Only approximately 20 global ports can fully accommodate ULCVs [4], leading to bottlenecks and increased reliance on transshipment operations [5]. Large floating transshipment terminals (LFTSTs), as illustrated in Fig. 1 [6], which are typically positioned offshore or near existing ports, can effectively mitigate congestion and improve cargo distribution efficiency. By positioning these terminals offshore or in sheltered waters, away from urban land constraints and dredging requirements, cargo exchange between ULCVs and smaller feeder vessels can be facilitated, improving the overall system fluidity. Such floating platforms represent an extension of very large floating structures (VLFSs), a field that has witnessed considerable development in offshore energy and military applications, but remains unproven in large-scale container logistics. As noted in previous conceptual studies [7], a full-scale LFTST has not yet been

developed, making it an emerging area of technical, regulatory, and economic inquiry.

This study aims to provide a critical commentary on the future role of LFTSTs as a transformative alternative to conventional port expansion. Rather than offering a conventional research framework, the discussion presents engineering feasibility, environmental performance, and socio-political challenges from the perspectives of infrastructure scalability and cross-sector deployment. The key considerations include structural concept designs, energy supply systems, hydrodynamic performance, and lifecycle costs. This study also emphasizes the importance of legal frameworks, stakeholder alignment, and seismic resilience, which are underexplored in the current literature.

The authors aim to provoke interdisciplinary discussions and propose a forward-looking agenda for achieving LFTSTs as climate-resilient, scalable infrastructure solutions in a world where maritime logistics must adapt to increasingly complex global pressures.

2. Motivations for large-scale floating transshipment terminals

2.1. Port congestion and infrastructure limitations

The rapid expansion of maritime trade has strained the existing port infrastructure, particularly in urbanized regions with limited space for expansion. The key challenges include:

- (1) Limited quay depth: Several ports lack the necessary depth to accommodate fully loaded ULCVs and thus require lightering or offshore cargo transfer.
- (2) Land scarcity [8]: Urbanization restricts the expansion of conventional port facilities.
- (3) Environmental restrictions: Dredging and land reclamation for port expansion often face regulatory hurdles owing to ecological concerns.

LFTSTs can alleviate these constraints by serving as offshore hubs for cargo transfer between the ULCVs and feeder ships.

2.2. Economic justifications

Floating terminals are a cost-effective alternative to conventional port expansion. Although land-based port development requires extensive dredging and land reclamation, LFTSTs eliminate these requirements, reducing the initial capital expenditure

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Fig. 1. Sea technology floating terminal, a floating terminal designed for large container transshipments. Reproduced from Ref. [6] with permission of Sea Technology B. Lundquist AB, ©2025.

(CAPEX) and long-term environmental costs [9]. Studies comparing floating and land-based transshipment hubs have shown that LFTSTs can reduce infrastructure investment by up to 30%, while maintaining or improving operational efficiency [8].

3. Historical development of large floating structures used for LFTSTs

Large floating structures have historical roots in ancient civilizations where waterborne platforms were employed for transportation, trade, and military purposes. Advancements in engineering and materials science have transformed large floating structures from rudimentary platforms to sophisticated solutions for urbanization, energy production, and maritime logistics. Today, they have a wide range of applications, including transshipment terminals, floating airports, residential development, renewable energy farms, and military installations.

The concept of floating cargo transfer dates back to the early 20th century, when simple barges were used for offshore cargo handling. With the expansion of maritime trade, the need for larger and more stable floating structures emerged. By the late 20th century, technological advancements facilitated the construction of semi-submersible floating platforms and deep-water cargo transfer terminals.

Significant historical milestones in LFTST development include the following:

- (1) World War II Mulberry harbors: Temporary floating ports were deployed for logistical support during the D-Day or Normandy landings on June 6, 1944.
- (2) Offshore oil and gas platforms: The development of floating storage and offloading units has inspired innovation in cargo handling.
- (3) Modern semi-submersible cargo platforms: They are enhanced-stability and wave-resistance platforms for reliable offshore transshipment operations.

These historical examples have laid the groundwork for contemporary innovations in VLFSS, a domain that has witnessed advances across multiple sectors, most notably in offshore energy, military installations, and urban expansion in coastal megacities.

Modern large-floating-structure applications include floating liquefied natural gas (FLNG) facilities such as the Prelude FLNG platform owned by Shell (Fremantle, Australia) [10], floating airports (e.g., Mega-Float in Tokyo Bay [11]), and semi-submersible offshore oil platforms. These structures have demonstrated the feasibility of deploying large-scale infrastructure on water; however, a dedicated LFTST has not yet been constructed or used for commercial operation [12]. The transition from oil- and gas-focused floating units to cargo-focused platforms has introduced unique

engineering challenges, including structural modularity, cargo-handling dynamics, and mooring under high-throughput loads.

Notably, the Mega-Float project [11] pioneered modular floating runway platforms using steel-box modules with hinge connections, demonstrating the potential for assembling and stabilizing large-scale deck areas. Although oil- and gas-focused FLNGs operate under harsh conditions, they benefit from the existing classification rules and ship-based design heritage, unlike the proposed LFTSTs, which would typically feature significantly larger beam-to-draft ratios and different motion profiles.

The development of LFTSTs necessitates a novel approach to integrating maritime engineering principles, encompassing hydro-elastic design, modularity, automation readiness, and long-term resilience, to justify their introduction into the global port infrastructure system.

4. Engineering and design considerations

4.1. Types of LFTSTs

A wide range of structural typologies can be envisioned for LFTSTs, each offering different tradeoffs in terms of construction feasibility, lifecycle cost, and hydrodynamic performance. The most prominent configurations are as follows:

- (1) Monolithic steel structures, which are large welded steel pontoons that provide high structural stiffness and ease of integration with standard port equipment, although they typically require rigorous corrosion protection and frequent maintenance.
- (2) Reinforced concrete caisson platforms, which leverage the long-term durability and passive corrosion resistance of concrete, offering extended service life with minimal maintenance; they are particularly suited for high-salinity or warm-water environments.
- (3) Modular hinged steel units are inspired by VLFS research, such as Mega-Float [13], in which individual modules are flexibly connected to accommodate wave-induced motions and ease of transport and assembly.
- (4) Semi-submersible or deep-draft platforms, which are adapted from offshore oil and gas technology, offer enhanced stability in rough sea states, but require deeper anchoring and complex mooring systems.
- (5) Hybrid systems combine concrete floats with steel superstructures, enabling performance and cost optimization for specific environmental or logistical constraints.

Each type is compatible with different deployment environments, from sheltered waters to semi-exposed offshore zones, and can be selected based on the regional fabrication capacity, environmental loading conditions, and modularity requirements for future expansion or relocation.

4.2. Structural design and stability performance

LFTSTs must be designed to withstand various marine environments, which are shaped by dynamic factors such as wave forces, currents, and extreme weather conditions. Sheltered waters (e.g., bays or fjords) are preferred because of their reduced wave loading and improved accessibility, although semi-exposed sites may be advantageous for major shipping lanes. The key structural considerations are as follows:

- (1) Platform dimensions: A typical LFTST design measures approximately a few hundred meters (e.g., 600 m × 400 m), providing sufficient space for container-handling operations.
- (2) Stability performance: Computational fluid dynamics and hydrodynamic modeling must be employed to optimize the platform movement and minimize operational disruptions. The

hydroelastic behavior of large floating structures is crucial for ensuring their stability under varying sea conditions, and both global motions and local deformations must be considered. Anti-motion devices, such as submerged heave plates and floating breakwaters, have been proposed to mitigate wave-induced motions, thereby ensuring smoother operation. Compared with intact stability, damage stability (e.g., in the event of compartment flooding) must be carefully addressed through internal subdivision, redundancy, and damage-tolerant design.

4.3. Mooring systems

Mooring design must account for both operational loads and rare extreme events (e.g., rogue waves and storm surges). The associated design strategies depend on site depth and environmental loads. The various mooring systems include the following:

(1) Catenary mooring systems with drag-embedded anchors or suction piles are suitable for shallow to moderate depths (10–50 m).

(2) Tension-leg mooring, which offers superior station keeping in deep water, is generally unsuitable for shallow deployment owing to vertical pretension demands and complex construction.

(3) Hybrid mooring systems that combine catenary chains and vertical dampers offer a practical compromise for semi-exposed sites.

Motion can be further mitigated using rubber fender–dolphin systems [14], breakwaters, or heave plates.

4.4. Towing logistics

The “weather window” for towing an LFTST from a manufacturing shipyard to the site of application must be carefully planned. Safe havens (ports of refuge), which are designated harbors or sheltered areas where ships can seek safety during inclement weather or emergencies, must be carefully planned, as they provide a place to avoid extreme weather conditions; in the absence of such areas, LFTSTs must be designed with excessive strength and rigidity. This is particularly important for structures whose dimensions (length, width, and depth) deviate significantly from those of conventional ships.

A modular or semi-modular construction approach, in which large segments are assembled at or near the final site, can reduce risks and costs while ensuring quality control. This planning helps to mitigate risks and ensures compliance with maritime safety regulations.

4.5. Cargo-handling systems

An efficient cargo transfer between ULCVs and feeder vessels requires automation and high-speed container-handling technologies. Previously proposed cargo-handling systems for LFTST include the following:

(1) Automated ship-to-shore (STS) cranes equipped with artificial intelligence (AI)-based logistics management to maximize throughput.

(2) Rubber-tired gantry (RTG) cranes facilitate container stacking and transfer operations.

(3) Automated guided vehicles (AGVs) reduce human intervention and optimize cargo movement.

4.6. Lifecycle planning and component replacement

Given the significant investment required for a floating platform of this size, ensuring a long operational lifespan is crucial. Engineers must design floating boxes and structural foundations to ensure durability and long-term performance.

Unlike conventional ships, an LFTST cannot be dry-docked for bottom inspections, making a comprehensive maintenance plan essential. A dedicated study [5] identified life-limiting factors, and based on stakeholder requirements, a technical lifespan of 60 years is a reasonable baseline for the primary floating-structure design.

Among the key factors that influence longevity, corrosion protection, and inspection strategies are the most significant. The study [5] categorized maintenance into three key phases: ① design-phase considerations—ensuring longevity through material selection and coatings; ② construction-phase measures—implementing protective systems during assembly; ③ ongoing maintenance strategies—establishing robust, risk-based inspection programs.

The findings of the study outline recommended strategies [5] for maintaining continuous, uninterrupted operations, along with cost estimates and stakeholder-aligned measures. They highlight corrosion and its mitigation as the primary determinants of the lifespan of a platform.

During their service life, the following subsystems and components will require periodic replacement or upgrades:

(1) Crane systems (e.g., STS and RTG): expected lifespan of 25–30 years depending on usage intensity.

(2) Coatings and corrosion protection: recoating intervals of 10–15 years, particularly in splash zones.

(3) Energy and utility systems: Power modules (small modular reactors (SMRs) or hybrid systems) may require refurbishment every 20–30 years.

To support inspection and maintenance without drydocking, the LFTST should incorporate the following: internal-access tunnels and compartments that are accessible to remotely operated vehicles, condition-based monitoring systems (e.g., strain gauges and acoustic emission sensors), and risk-based inspection schedules to prioritize high-risk zones and reduce lifecycle costs.

Designing by adopting the modularity concept [15], for example, removable deck panels or swappable crane mounts, can further facilitate component turnover and minimize service interruptions.

4.7. Design differences between LFTSTs and VLFSS

Modern LFTSTs employ cutting-edge structural designs to enhance stability, efficiency, and durability. LFTSTs can be categorized as a subset of VLFSSs, which are broadly defined as floating platforms with lengths typically exceeding 60 m and often reaching several hundred meters in length. However, compared with conventional VLFSSs, LFTSTs are uniquely engineered for cargo handling, dynamic loading from vessel operations, and integration with automated logistics systems. The major differences between the structures include the following:

(1) Load conditions: Although conventional VLFSSs are primarily subjected to environmental loads (waves, wind, and currents), LFTSTs must also endure dynamic loads from cranes, vehicles, and berthing ships.

(2) Mooring requirements: LFTSTs typically require more robust and adaptive mooring systems than other VLFSSs owing to their operational constraints and exposure to frequent berthing events.

(3) Deck configuration: In contrast to typical flat-decked VLFSSs, LFTSTs incorporate container stacking areas, crane rails, and reinforced berthing zones.

5. Energy supply and environmental considerations

The sustainable operation of an LFTST depends heavily on the integration of reliable and efficient energy systems that can

support intensive and continuous operations in remote or offshore environments. Owing to the scale and automation level of such platforms, the power demand is expected to be substantial, necessitating robust energy planning and system selection tailored to site-specific constraints and operational profiles.

5.1. Power demand and energy supply options

Based on preliminary estimates, a fully automated LFTST handling over two million TEUs annually will require peak power of approximately 100 MW, accounting for the major demands from the following: ① STS cranes; ② RTGs, AGVs, and yard operations; ③ reefer racks, lighting, heating, ventilation, and air-conditioning, and support systems.

Power must also be available with high reliability, given the sensitivity of automated operations to power outages or voltage fluctuations.

The primary power supply systems include:

(1) Diesel generators (baseline/backup): They exhibit the advantages of proven technology, flexible load response, and relatively low CAPEX; however, they result in high greenhouse gas emissions and noise pollution, and are limited by fuel-logistics complexity.

(2) SMRs: Their advantages include long-term low-carbon base load and minimal refueling frequency (every 5–10 years). However, they are limited by regulatory complexity, high upfront investment, and public resistance. A 20 MW-class SMR can supply a full terminal load. However, deployment strongly depends on licensing, nuclear waste logistics, and the integration of radiation safety protocols. Thorcon, founded by the former Massachusetts Institute of Technology (MIT) professor Jack Devanney, is one of the most advanced and deployment-ready SMR concepts. The molten salt reactor designed by Thorcon was intended for shipyard-based construction and barge-mounted deployment, allowing for nuclear energy generation from floating platforms. By leveraging mass-manufacturing techniques from commercial shipbuilding and incorporating passive safety features inherent to molten salt technology, Thorcon significantly reduces construction time and enhances scalability. The design has already reached a significant milestone, with the company applying to build the first commercial nuclear power plant in Indonesia, which is a 500 MW floating molten salt reactor, demonstrating both technical maturity and near-term regulatory traction. As illustrated in Fig. 2 [16], the Thorcon approach is uniquely aligned with the floating infrastructure vision of LFTSTs, offering a reliable, carbon-free base-load energy solution that can be directly integrated into offshore logistics ecosystems.



Fig. 2. Integration of Thorcon, the molten salt reactor power barge, into a shipyard-built hull, showing the floating SMR concept intended for tow-to-site deployment and seabed ballasting. Reproduced from Ref. [16] with permission of ThorCon US, Inc., ©2025.

(3) Offshore renewable energy integration (wind and solar energies) systems: These systems are ideal for hybrid or peak-shaving roles and exhibit strong alignment with public opinions and environmental, social, and governance standards. However, they are limited by intermittent output, variable weather dependency, and the need for auxiliary energy storage systems. Because of the limited energy capacity factor (average power output divided by its maximum power capability), floating wind and photovoltaic systems can supply 20%–40% of the demand seasonally, and they can work more efficiently when paired with battery storage (e.g., 40–100 MW·h⁻¹ Li-ion or flow battery systems) and/or SMR.

Fig. 3 illustrates the deployment of a fleet of floating offshore wind structures.

(4) Hydrogen fuel cells: They are a significantly attractive choice because of zero emissions at the point of use and their scalability. However, they exhibit disadvantages such as limited marine infrastructure for hydrogen delivery and storage and lower round-trip efficiency (~35%–45%) [17].

A hybrid solution combining renewables with SMRs or low-emission diesel engines as backup offers the most robust solution, ensuring reliability while decarbonizing baseline operations. Life-cycle carbon modeling suggests that switching from diesel to SMRs can reduce CO₂ emissions by up to 85% [9]. However, safety regulations and public acceptance remain barriers to implementation. Moreover, prioritized renewable energy strategies can eliminate fuel-related emissions when combined with large-scale energy storage systems.

Table 1 compares the key aspects of the different energy supply options for LFTSTs based on technical, economic, environmental, and operational criteria.

5.2. Environmental performance

Although LFTSTs offer significant sustainability advantages over land reclamation and dredge-intensive port expansion, they also introduce new environmental considerations.

The advantages include:

(1) Reduced marine dredging and landfilling as floating structures preserve seabed integrity and coastal morphology.

(2) Lower ship waiting time as offshore cargo exchanges reduce emissions from idling ULCVs near congested ports.

(3) Waste treatment capability: LFTSTs can be equipped with advanced blackwater/greywater treatment and ballast water management systems to reduce pollutant discharge and invasive species transfer. They are often designed as modular, closed-system platforms that facilitate centralized blackwater, greywater, and



Fig. 3. Offshore wind farm comprising a fleet of wind turbines and floating supporting structures (courtesy of Odfjell Oceanwind, Norway).

Supply option	Criteria							Backup requirement		
	Power supply stability	Typical scale	CAPEX	Operational cost	CO ₂ emissions	Technology maturity	Regulatory challenges		Deployment complexity	Environmental risks
Diesel generators	High	Modular	Low to moderate	High (fuel logistics, maintenance)	Very high	Mature	Standard maritime regulations	Low	Oil spill, air pollution	No
SMRs	Very high (base load)	Modular	Very high upfront	Low (long refueling cycle)	Very low	Emerging (pilot projects are ongoing)	Stringent nuclear licensing	High (radiation shielding, legal hurdles)	Radiation risks (low probability with high impact)	No (base load by nature)
Floating renewables (wind + solar)	Intermittent (weather dependent)	Scalable	Moderate (decreasing over time)	Low (wind and solar are "fuel-free")	Zero direct emissions	Mature for offshore wind; solar systems are maturing rapidly offshore	Grid integration, zoning conflicts	Moderate (anchoring, array maintenance)	Minimal (primarily visual and habitat)	Yes (energy storage or hybrid backup required)
Hydrogen fuel cells	Moderate (dependent on storage)	Modular (scalable in clusters)	High (for fuel infrastructure)	Moderate (hydrogen production/supply)	Zero direct emissions	Early stage for large marine use	Hydrogen safety regulations	High (supply chain development)	Minimal at point of use, upstream CO ₂ depends on hydrogen source	Yes (if supply interruptions occur)

Because LFTSTs occupy a hybrid legal space—fixed but buoyant, mobile yet not self-propelled—no direct precedent exists within the Safety of Life at Sea (SOLAS) or MARPOL conventions. A tailored classification standard, similar to those for offshore floating

production units (floating production, storage, and offloading/FLNG facilities), but adapted for cargo operations, must be developed.

Table 2 lists the major regulatory domains applicable to LFTSTs and highlights the primary compliance challenges in the offshore, maritime, and environmental contexts.

6.2. Regulatory distinctions: FLNG facility versus LFTST

Although similarities can be drawn between FLNG terminals (e.g., Prelude FLNG [10], Malacca Strait floating storage and regasification unit [19]) and LFTSTs, important differences must be recognized, which are briefly summarized in Table 3.

Thus, although valuable lessons can be drawn from FLNGs, regulatory modeling for LFTSTs must address different load cases, operational risks, and ecosystem interactions.

6.3. Commercial potential and economic outlook

An early example of a floating-port concept is the sea technology floating terminal, which was developed through a collaboration between the longstanding naval architect and innovator Bengt Lundqvist (Sweden, the concept designer behind the STFT), Det Norske Veritas (DNV; Norway), and three major Republic of Korea shipyards. Lundqvist applied concurrent engineering methods [20] to rapidly evaluate and discard unfeasible alternatives, and engaged closely with technical and commercial partners in iterative design loops. After two years of intensive coordination, the consortium secured preliminary construction offers from shipyards, demonstrating both the technical feasibility and early commercial traction of large-scale floating terminal designs.

The commercial viability of LFTSTs hinges on achieving a favorable balance between the initial investment, operational revenues, and lifecycle costs. Early concept studies, such as those developed by Sea Technology B. Lundqvist Aktiebolag [12], suggest potential CAPEX values in the order of 2.5 billion USD for a 20 000–25 000 TEU capacity floating terminal, including platform construction,

cargo handling equipment, mooring systems, and supporting utilities.

Potential revenue streams include transshipment fees charged per container moved, stevedoring and feeder service charges, fees for on-platform ancillary services such as bunkering, reefer cargo handling, and equipment maintenance, as well as charges levied for energy supply and storage leasing, if surplus renewable energy integration is achieved.

Preliminary estimates suggest that, assuming a throughput of four million TEUs annually, the payback period could range from 11 to 12 years, depending on operating margins, financing structures, and regional logistics demands.

Key commercial advantages include access to strategic offshore locations that are not constrained by land availability, de-risking of major hub ports by decentralizing cargo flows, and enhanced resilience to climate-induced risks (e.g., sea-level rise, coastal storm surges).

However, capital risk, insurance cost premiums (particularly if SMRs are involved), and the market acceptance among shipping alliances remain significant hurdles. Public-private partnership models, green financing mechanisms, and long-term cargo throughput guarantees are likely to be critical for securing financial closures.

7. Critical challenges and future research directions

A comprehensive understanding of the unresolved challenges faced by the LFTSTs is essential for their successful implementation. Although substantial advances have been made in marine engineering, numerous scientific and engineering questions remain unanswered, including those related to structural dynamics, system integration, environmental resilience, and energy management. As concepts such as sea technology floating terminal gain traction in the maritime and logistics sectors, project development is expected to follow a concurrent engineering approach, in which critical tasks proceed simultaneously rather than sequentially.

Table 2

Summary of regulatory frameworks and key compliance considerations for LFTSTs.

Regulatory area	Relevant authority/framework	Key issues for LFTSTs
Maritime navigation	IMO and port authorities	Navigational safety, berth licensing, and towage permits
Offshore energy development	Offshore wind regulators and seabed authorities	Seabed-use rights and spatial conflict with offshore energy zones
Environmental protection	National environmental protection agencies, UNCLOS Annex V, MARPOL	Habitat impact, pollution control, and ballast water management
Structural classification	Det Norske Veritas (DNV), American Bureau of Shipping (ABS), Lloyd's Register	Need for new hybrid-class rules (offshore + port handling)
Occupational safety and operations	National labor & safety bodies (e.g., Occupational Safety and Health Administration equivalents)	Crew safety, cargo operation standards, and emergency preparedness
Nuclear energy (if SMR is used)	National nuclear regulatory agencies (e.g., United States Nuclear Regulatory Commission, Canadian Nuclear Safety Commission)	SMR siting, radiation protection, and licensing complexity
Insurance and risk management	Marine insurance market (Protection & Indemnity Clubs, Lloyd's Market)	Defining coverage terms for a hybrid port/offshore asset

Table 3

Major differences between FLNG terminals (e.g., Prelude FLNG [10], Malacca Strait floating storage and regasification unit [19]) and LFTSTs.

Type	Aspect				
	Classification basis	Structural characteristics	Regulatory maturity	Operational load type	Zoning and siting
FLNG facilities	Ship rules (SOLAS/IMO) + offshore class (e.g., DNV, ABS)	Deep draft, ship shaped, and designed for harsh sea states	Extensive precedence from oil & gas sector	Fluid handling (storage & processing)	Typically, outside major shipping lanes
LFTSTs for container shipping	Likely require new hybrid classification: port + offshore platform	Wide, shallow draft, and highly hydro-elastic; more vulnerable to dynamic loadings	Nascent; no built examples; and regulatory pathways are underdefined	Cargo handling	Must integrate with heavy shipping traffic and regional port networks

Once customer commitment and financial backing are secured, engineering efforts will intensify to resolve outstanding technical issues, including hull design, automation integration, platform motion control, and energy supply systems. Regulatory engagement at both the international and national levels is crucial in the early stages to validate siting feasibility and safety compliance. With an estimated construction lead time of approximately three years, sufficient opportunity is available to refine system specifications, program autonomous cargo-handling operations, and optimize intermodal logistics, provided that these elements remain aligned with stakeholder expectations and project constraints.

7.1. Engineering challenges in hydrodynamic and structural analysis

7.1.1. Nonlinear wave loads and floating body response

The large footprint and substantial mass of LFTSTs introduce new complexities in the structural mechanics and fluid–structure interactions. Unlike oil platforms or floating wind turbines, LFTSTs involve coupled cargo handling operations and high deck loads with the frequent movement of ULCVs. Accurate modeling of wave-induced responses, dynamic positioning during berthing, and mooring-induced vibrations are critical.

LFTSTs operate in deep-sea environments where they must withstand complex waves, wind, and current loads. The nonlinear interaction between the waves and floating structure results in strong fluid–structure coupling effects, including:

(1) Large-amplitude motion: Under extreme sea conditions (e.g., typhoons and high waves), a floating platform may experience severe pitching, rolling, and heaving motions.

(2) Slamming loads: Large-wave impacts on the bottom and sides of the structure can cause local damage and affect the fatigue life.

(3) Wave run-up and green water effects: Certain areas of the platform may experience significant wave run-up or even deck inundation, affecting operational safety.

Therefore, more efforts must be expended in developing the following: ① efficient methods to perform fully coupled time-domain simulations incorporating hydrodynamics, mooring systems, and real-time cargo transfer dynamics; ② scalable structural modularization strategies to ensure redundancy and rapid assembly while maintaining global stiffness; ③ hull shape optimization to reduce motion responses and improve seaworthiness.

7.1.2. Fatigue and long-term structural monitoring

As LFTSTs are exposed to sea environments for extended periods, the cyclic effects of wave and wind loads can lead to significant fatigue damage, thereby affecting their service life. Key challenges include:

(1) Fatigue life assessment: Rather than using the conventional stress-life approach, fracture mechanics analysis must be adopted to predict fatigue failure in critical structural areas such as welds and connection points [21].

(2) Corrosion and material degradation: Marine environments accelerate corrosion, necessitating the use of advanced protective coatings and real-time monitoring using electrochemical sensors.

(3) Maintenance and repair strategies: Robotic underwater inspections and drone-based monitoring must be implemented to enhance maintenance efficiency.

7.2. Seismic and tsunami resilience: A comparative advantage

Owing to their buoyant, decoupled configuration, LFTSTs, being both floating and moored, offer intrinsic advantages in terms of earthquake and tsunami resilience compared with land-based ports. During seismic events, floating terminals experience decou-

pling from ground accelerations. Similarly, tsunami forces are largely absorbed through relative motion between the floating structure and its mooring or tethering systems, significantly reducing the structural risk. Moreover, when LFTSTs are located in deep-water areas, the magnitude of tsunami forces is drastically reduced [22]. Unlike land-based ports, which are directly exposed to soil liquefaction, quay wall failure, and ground subsidence during earthquakes, LFTSTs float above fault lines and can absorb and dissipate seismic energy without structural ruptures. A stark example is the Port of Sendai in Japan, which was severely damaged during the 2011 Tōhoku earthquake and tsunami. The port experienced extensive quay wall collapse, container terminal submergence, and long-term disruption of logistics services despite being built according to modern seismic codes. Conversely, floating structures in the nearby Miyagi Prefecture (Japan), such as offshore fish farms and buoyed docks, sustained minimal damage, largely owing to their hydrodynamic compliance [23]. This comparison underscores the potential of LFTSTs as disaster-resilient logistics infrastructure, particularly in tectonically active regions such as the Pacific Ring of Fire or Andean coast.

However, several research gaps remain such as: ① difficulty in quantification of tsunami-induced mooring loads under extreme run-up conditions and wave amplification near coastal shelves; ② lack of performance-based designs of flexible mooring and energy dissipation systems that are capable of withstanding rare but catastrophic events; ③ limited and fragmented comparison of post-event operational recoverability between floating terminals and land-based ports, focusing on downtime, structural integrity, and economic loss; ④ lack of a risk assessment framework that integrates seismic hazard models, tsunami propagation dynamics, and mooring system reliability, which can significantly strengthen safety case justifications [22].

7.3. High capital and maintenance costs

One of the most significant limitations of LFTSTs is their high initial capital investment requirements. Constructing a floating terminal that is capable of handling ULCVs requires advanced engineering, specialized materials, and state-of-the-art cargo-handling systems. For example, mooring systems, anti-motion devices, and automated cranes are prohibitively expensive. Moreover, the long-term maintenance costs are substantial as these structures are exposed to harsh marine environments, leading to corrosion and wear. Unlike conventional ships, LFTSTs cannot be dry-docked for repair, necessitating expensive underwater maintenance and inspection programs.

Several targeted research directions can be pursued to address these challenges. They aim to optimize the design, extend service life, and reduce long-term operational expenses. They are as listed subsequently:

(1) Modular and prefabricated construction techniques: Scalable modular platform designs that allow off-site prefabrication and rapid onsite assembly should be developed. Research should focus on lightweight high-strength composite materials and hybrid steel–concrete modules for structural components to reduce material and fabrication costs.

(2) Corrosion- and biofouling-resistant and maintenance-free materials: Advanced coatings, high-performance marine alloys, and self-healing materials (which autonomously address minor damages or cracking) that can reduce the frequency and cost of inspections and maintenance should be investigated. Cathodic protection systems and environmentally friendly antifouling technologies that are optimized for long-term submersion should be promoted.

(3) Smart structural health monitoring: The implementation of sensor networks, AI-driven predictive maintenance algorithms, and digital twin models can enable condition-based rather than schedule-based maintenance. Damage localization and fatigue life prediction must prioritize repair tasks and reduce lifecycle costs.

(4) Optimized mooring and positioning systems: Hybrid mooring systems with reduced dynamic loads should be studied to enable less robust anchoring hardware and simpler maintenance access. Real-time environmental monitoring should be integrated to dynamically adjust tension loads and minimize wear.

(5) Multiuse platform concepts: The economic co-location of other functions, such as aquaculture, offshore wind maintenance hubs, and data centers, should be explored to share construction and maintenance costs across sectors. Design-adaptable layouts that allow for shifting functions over time as trade patterns and market demands evolve should be considered.

(6) Automation and workforce reduction: Cost-effective robotic cargo handling, AI-assisted logistics coordination, and autonomous inspection drones should be developed to reduce reliance on offshore labor. Research should focus on developing fail-safe automation systems that require minimal operator intervention.

(7) Lifecycle cost optimization and circular design: End-of-life reuse, modular decommissioning strategies, and recyclable components should be incorporated into the initial design to reduce the total ownership cost. A full lifecycle cost-benefit analysis should be conducted early in the design phase using parametric modeling tools.

(8) Digital twin and predictive maintenance: Given their operational complexity, LFTSTs can significantly benefit from digital twin technologies. A digital twin integrates real-time sensor data with structural models to predict maintenance requirements, operational performance, and emergent failures.

Research in this domain should aim to: ① develop high-fidelity digital twin architectures [24] incorporating multi-physics simulation and machine learning; ② enable real-time anomaly detection and condition-based maintenance for mooring systems, hull integrity, and onboard equipment [25,26]; ③ create open-source digital ecosystems for standardization and interoperability across floating logistics assets.

7.4. Regulatory and environmental challenges

The deployment of LFTSTs is subject to stringent regulatory hurdles, particularly concerning safety, emissions, and environmental impact. For instance, although promising, the integration of SMRs for energy supply faces significant regulatory barriers owing to safety concerns and public opposition. Furthermore, the environmental impacts of LFTSTs, such as potential disruptions to marine ecosystems and the risk of oil or chemical spills, must be mitigated. Although LFTSTs reduce port congestion, their construction and operation can lead to localized environmental degradation, such as increased noise pollution and habitat disruption.

To address the aforementioned regulatory and environmental challenges, the following four research directions are proposed:

(1) Development of integrated environmental impact models. **Objective:** to support regulatory approval and stakeholder engagement through transparent environmental assessments. **Approach:** create high-resolution ecosystem simulation tools [27] to model the long-term impacts of LFTSTs on local marine biodiversity, sediment transport, and acoustic environments. Combine lifecycle assessments with agent-based modeling to predict ecological footprints and inform mitigation strategies for noise, lighting, and habitat disruption.

(2) Incorporation of risk-informed SMR integration frameworks. **Objective:** to enable regulatory acceptance of SMRs for offshore energy use. **Approach:** develop failsafe deployment strategies and floating containment architectures to isolate SMR units from cargo operations. Collaborate with nuclear agencies to design offshore-specific licensing pathways that incorporate passive safety systems and remote emergency shutdown protocols. Investigate public acceptance frameworks using a comparative risk analysis versus conventional marine fuels.

(3) Designing structures that ensure environmental resilience and biodiversity neutrality. **Objective:** to minimize environmental degradation caused by floating infrastructure. **Approach:** integrate bio-inclusive designs, such as artificial reefs and fish aggregation devices, on submerged surfaces to support marine life. Use low-impact anchoring systems (e.g., suction piles or dynamic positioning) to avoid seabed scouring [28] in sensitive habitats. Develop acoustic dampening materials and structural designs to reduce underwater noise emissions.

(4) Application of smart monitoring and compliance systems. **Objective:** to ensure real-time environmental compliance and transparent reporting. **Approach:** implement monitoring systems for emissions, effluents, and ecological disturbances. Utilize block-chain-enabled environmental reporting [29] to share data with regulators and stakeholders in real-time, thereby enhancing trust and auditability. Enable automated deviation detection and alerts, facilitating adaptive management and reducing the risk of noncompliance.

7.5. Operational and logistical constraints

LFTSTs encounter operational challenges related to their stability and efficiency under varying sea conditions and logistics. Once an LFTST is ordered for a particular location, these constraints must be addressed to minimize off-hire. The finalized design should aim for a sheltered location with a predefined maximum allowable significant wave height. The offshore LFTST may benefit from less wind turbulence during high-wind conditions than the nearby shore port, a physical circumstance that will appear in the simulations for each location. If an LFTST is required in an open-sea area, significant engineering and construction work may be necessary to prevent resonance with swell waves, as this demands a prohibitively high global flexural stiffness in the design.

Key research areas to cope with the operational and logistic constraints include:

(1) Site-specific metocean simulation and design optimization. **Objective:** to ensure the stable and uninterrupted operation of LFTSTs by matching their design to localized environmental conditions. **Approach:** develop high-resolution coupled wave-current-wind models to simulate the operational performance of LFTSTs under various sea states, wind profiles, and seasonal patterns. Utilize probabilistic weather routing and downtime analysis to establish design thresholds for significant wave height, mooring loads, and crane operability. Apply multi-objective optimization algorithms to balance structural stability, cost, and logistics based on regional metocean databases.

(2) Advanced motion compensation and mooring technologies. **Objective:** to improve the cargo-handling efficiency and structural stability of LFTSTs in mildly rough seas. **Approach:** research active or semi-active motion-damping systems [22], such as tuned mass dampers or gyro-stabilizers, tailored for large-scale floating platforms. Investigate adaptive mooring systems [30,31], such as tension-leg hybrids or dynamically tuned moorings, which can

self-adjust based on real-time sea-state measurements, showing promise for enhancing the station-keeping performance of floating terminals. These systems adjust the mooring stiffness and damping properties in real-time to reduce fatigue loads and motion responses under dynamic wave conditions. Develop motion-tolerant cargo transfer systems (e.g., automated gangways, heave-compensated cranes, and magnetic locking mechanisms) [32–34] to minimize downtime due to vessel movement.

(3) AI-enabled operational logistics and forecasting tools. **Objective:** to enhance scheduling accuracy, reduce vessel queuing, and optimize transshipment workflows. **Approach:** implement digital twin frameworks [35] combining real-time sensor inputs, operational logs, and weather forecasts to dynamically simulate and optimize LFTST operations. Use AI-powered decision support systems [3,36] to allocate resources, predict berthing windows, and anticipate weather-induced disruptions.

7.6. Conflicts with military use of maritime space

The placement of LFTSTs must account for possible conflicts with the military use of maritime spaces, particularly in regions with active naval routes, surveillance zones, or strategic choke-points. Many coastal states maintain restricted maritime zones for defense operations, radar surveillance, and underwater infrastructure (e.g., submarine cables or sonar arrays), which may not be compatible with the long-term stationing of large floating platforms. Moreover, the presence of a high-volume civilian logistics infrastructure near sensitive military installations may raise security concerns, including access control issues, surveillance vulnerability, and dual-use ambiguity. To mitigate these risks, LFTST developers must engage in early consultations with national defense authorities and incorporate maritime spatial planning tools to ensure alignment with defense priorities. In high-tension or disputed waters, the deployment of LFTSTs may increase geopolitical sensitivity or trigger objections under existing naval treaties.

7.7. Critical perspectives and recommendations

Although a wide range of structural typologies and energy systems have been explored for LFTSTs, the current evidence suggests that a universally applicable solution does not exist. Instead, the optimal configurations must be tailored to regional operational contexts.

In Southeast Asia, where maritime logistics are dense, wave conditions are moderate, and grid access may be limited, semi-submersible steel platforms with floating solar photovoltaic integration and diesel-renewable hybrid power systems are the most practical. Their mobility, shallow draft requirements, and lower CAPEX align well with archipelagic transport needs and investment profiles.

Conversely, Northern Europe, with its harsh sea environment, mature offshore wind sector, and strict decarbonization targets, would benefit from concrete VLFs equipped with grid-connected offshore winds or SMRs. These regions can absorb higher upfront investments in exchange for long-term resilience, lower emissions, and climatic robustness.

Despite these technological advances, the slow pace of regulatory adaptation remains a critical barrier to their deployment. Current frameworks treat floating terminals as either ships (under SOLAS and MARPOL) or offshore energy units (under the Convention for the Protection of the Marine Environment of the North-East Atlantic or UNCLOS), neither of which fully accounts for hybrid floating-port platforms. Particularly, the lack of classification standards for multiuse floating terminals and legal ambiguity of energy-generation-capable logistics structures in the exclusive

economic zone create procedural uncertainty and risk for investors and developers.

Therefore, a more proactive approach is required. The IMO, in collaboration with the International Atomic Energy Agency and classification societies, such as DNV and American Bureau of Shipping, should develop a dedicated code of practice for floating logistics infrastructure, including design loads, environmental protection, and operational standards. Furthermore, regional bodies, such as the Association of Southeast Asian Nations, European Maritime Safety Agency, and African Union Maritime Taskforce, should establish pre-approved marine spatial zones for LFTSTs to streamline siting and de-risk investments.

Without coordinated policy reform and clearer regulatory pathways, the risk remains that LFTST innovation will remain trapped in the pilot phase, despite the clear economic and climate-resilience benefits offered by these systems.

Simultaneously, the widespread adoption of automated systems aboard LFTSTs, such as AI-enabled cranes, AGVs, and automated berthing, will inevitably disrupt conventional port labor structures. Dockworkers, crane operators, and stevedores may face significant job displacement as offshore operations reduce the need for large onsite human labor. Although this transition enhances efficiency, it raises concerns about socioeconomic inequality, particularly in regions where port employment is a major source of livelihood. To ensure a just transition, the future deployment of LFTSTs must be accompanied by strategic workforce retraining programs that are designed in collaboration with maritime labor unions, training institutions, and port authorities. Such programs should prioritize upskilling in digital logistics, remote platform monitoring, maritime cybersecurity, and offshore maintenance technologies. Moreover, national governments and international organizations, such as the International Labor Organization and IMO, should develop policy safeguards, including employment guarantees, phased automation timelines, and social protection frameworks, to buffer against abrupt labor shocks. Without such measures, the sociotechnical benefits of LFTSTs may come at the cost of eroded labor resilience and growing public resistance to automation-driven infrastructure.

7.8. Logistics automation and real-time control

LFTSTs require seamless operation of automated loading and unloading systems, AI-enabled container tracking, and ship-to-ship transshipment logistics under dynamically changing sea states. The integration of these components into a nonstationary floating environment poses several challenges.

Key research areas include adaptive control algorithms [37] for autonomous cranes and vehicles operating under small-amplitude platform motion, edge computing and resilient communication protocols for low-latency logistics coordination [38], and maritime cyber-physical security systems [39] tailored for offshore logistics hubs.

7.9. Integration with renewable energy systems

The envisioned coupling of LFTSTs with a floating renewable energy infrastructure, such as floating offshore wind farms or hybrid SMR systems, requires careful integration of energy supply, storage, and redundancy systems. Ensuring a reliable and uninterrupted energy supply for round-the-clock terminal operations, while simultaneously mitigating associated environmental risks, is essential.

The research challenges include optimal energy management under an intermittent renewable supply, with hybrid systems incorporating batteries or hydrogen storage, offshore electrical grid

architecture for isolated LFTST operation with minimal maintenance, and fault tolerance and remote diagnostics in marine energy systems that are exposed to corrosion, biofouling, and high humidity.

7.10. Environmental and regulatory considerations

Floating terminals must comply with the international marine pollution (e.g., MARPOL), safety (e.g., SOLAS), and port operation (e.g., IMO) standards, which were originally designed for ships or land-based ports. LFTSTs fall into a regulatory gray zone, which complicates their classification and compliance specifications.

Necessary investigations include the following: ① development of a new regulatory framework for “stationary floating-port structures” that combines rules from floating production units, seafaring vessels, and shore-based terminals; ② offshore environmental impact modeling to account for sediment displacement, thermal plumes from energy systems, and spill containment strategies; ③ lifecycle carbon accounting and circular design pathways to enable sustainable decommissioning or repurposing.

7.11. Public acceptance and stakeholder alignment

Public perception and stakeholder alignment are critical for the success of LFTSTs. Local communities and environmental groups may oppose such projects because of concerns about visual pollution, safety risks, and environmental impacts. Moreover, the shift toward automated systems (e.g., AI-driven cranes and AGVs) risks displacing conventional port labor, necessitating policies for workforce retraining and equitable transitions.

7.12. Socioeconomic and geopolitical challenges

The adoption of LFTSTs has significant socioeconomic and geopolitical implications. On the socioeconomic front, increased automation in cargo handling, such as AI-driven cranes and AGVs, will displace labor in conventional ports, exacerbating job insecurity for dockworkers. Although automation enhances efficiency, policymakers must implement workforce retraining and equitable transition strategies to mitigate social disruption.

Geopolitically, offshore LFTSTs may be vulnerable to security threats, including piracy, cyberattacks on automated systems, and territorial disputes over maritime jurisdictions. Their strategic placement in international waters can also increase competition among global shipping powers. Transparent governance and international cooperation are vital for mitigating these issues. Proactive governance frameworks, including international security protocols and labor protection policies, are essential to ensure that LFTSTs contribute sustainably to global trade without destabilizing the socioeconomic or geopolitical equilibria.

8. Conclusions and future outlook

LFTSTs offer a practical and scalable solution for addressing global port congestion by alleviating the critical infrastructure constraints faced by conventional ports. These platforms can enhance maritime trade efficiency and sustainability by integrating advanced logistics, automation, and renewable energy solutions.

This study highlights the current state-of-the-art developments in LFTST, including platform layout, energy integration strategies, environmental considerations, and key technological components. The major scientific, regulatory, and economic challenges that inhibit large-scale deployment are also discussed. Of particular signif-

icance is the resilience advantage of LFTSTs in geohazard-prone regions; this is because, unlike rigid coastal structures, floating terminals inherently decouple from seismic ground motion and dissipate energy from tsunamis owing to their buoyant nature. This results in superior performance in earthquake-prone and low-lying coastal zones compared with that of conventional fixed ports.

Realizing the potential of LFTSTs requires coordinated advances across multiple research areas and industrial disciplines. Six key areas of development are expected to play essential roles in shaping the next development of LFTSTs:

(1) **AI-driven logistics and predictive analytics.** The integration of AI into LFTST operations can significantly enhance efficiency and decision-making. AI-driven logistics systems can optimize cargo handling, predict maintenance requirements, and improve resource allocation. For example, predictive analytics can forecast peak operational periods, thereby enabling better scheduling of feeder ships and reducing idle time. Moreover, AI can enhance safety by continuously monitoring environmental conditions and adjusting operations in real-time to mitigate risks.

(2) **Autonomous cargo-handling systems.** The adoption of autonomous technologies, such as AGVs and robotic cranes, can further streamline cargo transfer operations. These systems reduce human intervention, minimize errors, and increase throughput. For instance, autonomous cranes equipped with AI-based logistics management can optimize container stacking and retrieval, thereby ensuring faster turnaround times for vessels. The development of fully autonomous LFTSTs that are capable of operating with minimal human intervention can revolutionize maritime logistics.

(3) **Integration of green energy and SMRs.** The incorporation of green energy sources, such as offshore wind and solar farms, coupled with energy storage systems, can provide sustainable power solutions for LFTSTs. SMRs offer a promising alternative for meeting the high-energy demands of these terminals. Although regulatory approval and public acceptance remain challenging, pilot projects and collaborative research can pave the way for their adoption. The successful integration of SMRs can reduce carbon emissions by up to 85% [9], making LFTSTs a cornerstone of green maritime infrastructure.

(4) **Regulatory and policy frameworks.** The deployment of LFTSTs requires clear regulatory pathways and international collaboration. Governments, port authorities, and classification societies must collaborate to establish standardized guidelines for safety, emissions, and environmental impacts. For example, the IMO should develop specific regulations for floating terminals to address unique challenges such as stability in harsh marine environments and the integration of advanced technologies.

(5) **Public engagement and stakeholder collaboration.** Public perceptions and stakeholder alignment are critical for the success of LFTSTs. Transparent communication and robust stakeholder engagement can address concerns related to safety, environmental impact, and visual pollution. For instance, community outreach programs and environmental impact assessments can build trust and foster public support for LFTST projects.

(6) **Socioeconomic and geopolitical safeguards.** Future research should prioritize two critical dimensions: ① the development of unbiased transition policies to mitigate labor displacement caused by automation, ensuring equitable workforce adaptation through reskilling initiatives and social safeguards; ② rigorous assessment of geopolitical risks, including the formulation of robust maritime security frameworks and conflict-resolution mechanisms for strategic waterways, where LFTSTs may exacerbate territorial tensions. Pilot projects must adopt inclusive stakeholder engagement protocols, incorporating inputs from

governments, industry, labor unions, and coastal communities, to optimize operational efficiency while safeguarding socioeconomic equity and regional stability.

LFTSTs stand at the intersection of offshore engineering, maritime logistics, and sustainable infrastructure. Although the technical feasibility of such systems is increasingly being validated through prototypes and simulation studies, their full-scale deployment hinges on addressing interdisciplinary challenges that span materials science, marine policy, automation, and environmental stewardship. A robust roadmap that integrates real-world demonstrator projects, international regulations, and public-private partnerships is essential. If realized, LFTSTs could redefine global maritime trade, unlocking capacity, flexibility, and resilience for the next generation of ocean-based infrastructure.

CRediT authorship contribution statement

Anders Ulfvarson: Writing – review & editing, Writing – original draft, Methodology, Investigation. **Junbo Jia:** Writing – review & editing, Writing – original draft, Methodology, Investigation.

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