



LNG PLANT DESIGN AND MODULARIZATION FROM PROJECT MANAGEMENT PROSPECTIVE

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ABSTRACT

Modularization changes how Liquefied Natural Gas (LNG) plants are engineered, fabricated, transported, and commissioned. Its technical value depends on whether process requirements and construction constraints are resolved together. This paper reviews the relationship between LNG plant design and modular execution, focusing on feed treatment, liquefaction configuration, equipment integration, module boundaries, structural design, piping flexibility, safety, fabrication quality, and operational readiness. Peer-reviewed engineering research and conference papers provide the principal literature base, supported by relevant standards and institutional guidance. The review identifies interface control, early logistics definition, verified equipment data, and system-based completion as recurring requirements for successful implementation. Illustrative calculations explain how thermal contraction and transport acceleration can influence module design; they are not project design criteria. A global perspective considers climatic, geotechnical, fabrication, and workforce differences without assuming that one module arrangement suits every location. The central conclusion is that modularization should be developed as part of the plant architecture, with technical performance and lifecycle integrity taking precedence over maximizing offsite assembly.

Keywords: Project Management, Schedule, Cost, Control, Transforming, Strategic Planning

1 INTRODUCTION

An LNG liquefaction plant removes heat from treated natural gas until it becomes liquid, commonly near minus 162 degrees Celsius at approximately atmospheric pressure. Behind this familiar description lies a tightly coupled engineering system. Treatment units protect cryogenic equipment; refrigerant circuits establish cooling duties; compressors supply mechanical work; and utilities, controls, and protective systems sustain the process. Lim, Choi, and Moon review the breadth of these plant-design decisions and the importance of evaluating configurations beyond their final product temperature [1].

Modularization adds a second architecture. Equipment and supporting systems are grouped into assemblies that can be fabricated away from the final site and installed as larger units. A module may contain a process package, a pipe rack, electrical equipment, or several connected functions. A liquefaction train, by contrast, describes a processing line. One train may contain many modules, and a module need not represent an independently operable train. Confusing these definitions can distort discussions about flexibility and repetition.

The attraction is straightforward: fabrication and site preparation can proceed concurrently, and some work can move into more controlled environments. The difficulty is equally real. Assemblies must survive handling, fit their foundations, connect accurately, remain maintainable, and operate safely after transport restraints are removed. Offsite completion transfers work; it does not remove engineering responsibilities.

Research by O'Connor, O'Brien, and Choi identifies organizational and execution conditions supporting industrial modularization [2, 3]. For LNG plants, those conditions must be combined with cryogenic integrity and process safety. The governing principle is to design the plant and its construction method together. A technically sound module is one that remains suitable through fabrication, movement, installation, startup, and service.

2 REVIEW METHOD AND EVIDENCE BOUNDARIES

This paper uses a targeted narrative review rather than a systematic review or a statistical meta-analysis. Sources were selected for direct relevance to liquefaction engineering, industrial modularization, construction integration, or equipment integrity. Peer-reviewed journal articles and specialist conference papers were prioritized. Standards and institutional guidance supplement the literature where design obligations, testing practices, or protective-system lifecycles require authoritative treatment.

Three evidence categories are distinguished. Process studies explain thermodynamic relationships and optimization methods. Construction studies address execution, standardization, work packaging, and information management. Equipment and safety publications examine particular failure mechanisms or protective approaches. Their findings are interpreted within their stated scope; results from one process simulation or construction dataset are not treated as universal performance guarantees.

The paper presents an engineering synthesis, not new experimental results. Recommendations concerning module interfaces and acceptance checks connect published concepts with conventional multidisciplinary design practice. The numerical examples are deliberately simplified and labelled as illustrative. Actual projects require validated property data, approved load combinations, supplier information, applicable regulations, and competent engineering review. References to standards indicate their relevant scope, not confirmation that every requirement has been reproduced or that one jurisdiction's rules apply globally.

3 ESTABLISHING A COMMON DESIGN BASIS

The design basis should define a feed envelope rather than a single representative composition. Relevant variables include pressure, temperature, flow, carbon dioxide, sulfur compounds, water, mercury, nitrogen, heavier hydrocarbons, and credible liquid carryover. Engineers also need product requirements, ambient conditions, availability objectives, operating modes, and assumptions about feed changes over the plant's life. Each item affects equipment duties and can influence module dimensions or interfaces.

Gas treatment establishes the boundary conditions for refrigeration. Acid-gas removal, dehydration, contaminants removal, and hydrocarbon separation should be evaluated as an integrated sequence. Water and carbon dioxide can create solid-formation problems at cryogenic conditions; mercury can damage susceptible aluminum equipment. Adsorbent beds, regeneration systems, separation vessels, and associated valves need enough operating flexibility to maintain acceptable feed quality during expected variations.

Santos and colleagues investigate molecular-sieve dehydration under changing carbon dioxide content [4]. The relevant lesson for design is that treatment performance cannot be specified independently of composition. A standard dehydration module still needs verification against its actual inlet conditions, regeneration requirements, pressure loss, and switching sequence. Reusing its geometry does not establish its suitability for another feed.

The same discipline applies to ambient conditions. Summer temperatures can govern cooling and driver performance, while winter conditions may govern minimum material temperatures, icing protection, and instrument arrangements. Rainfall, wind, seismic demand, groundwater, and settlement influence foundations and temporary works. Transport conditions introduce additional cases that permanent plant operation alone will not capture.

A common case register should connect these assumptions across disciplines. Process, mechanical, structural, piping, electrical, and construction teams should use consistent scenarios and controlled revisions. If a compressor package grows heavier or a cooler requires more area, the consequences must reach the module model, lifting study, foundation design, and delivery plan. Resolving uncertainty early is preferable to applying unrelated margins throughout the plant.

4 LIQUEFACTION CONFIGURATION AND MODULAR COMPATIBILITY

Liquefaction configurations include single mixed refrigerant, propane-precooled mixed refrigerant, dual mixed refrigerant, cascade, and expansion-based processes. These families differ in refrigerant circuits, compression arrangements, exchanger duties, operating flexibility, and equipment count. Zhang and colleagues compare process characteristics across different applications [5]. Their technical comparisons support selection against a defined operating envelope rather than a universal ranking of technologies.

Modular compatibility should be assessed during that selection. A compact process may reduce equipment count but concentrate dependencies within one package. A configuration with several refrigerant circuits may create more interfaces while offering clearer functional groupings. Neither outcome is inherently superior. Designers must examine equipment geometry, maintenance space, pressure losses, control interactions, and the feasibility of fabrication and installation.

Thermodynamic comparisons need consistent boundaries. Specific energy consumption should state whether it includes only refrigerant compression or also treatment, utilities, and electrical losses. Feed conditions, product conditions, compressor efficiencies, exchanger assumptions, and ambient temperatures must be comparable. Otherwise, an apparent process advantage may reflect different assumptions rather than better design.

Watson and colleagues demonstrate optimization that explicitly accounts for multi-stream exchanger area and detailed cooling curves [6]. Wu and colleagues examine optimization of a single-stage mixed refrigerant process [7]. These studies illustrate the importance of interacting variables; they do not establish the best equipment arrangement for every site. A lower simulated compressor duty still requires credible exchanger geometry, suitable compressor maps, and manageable control behavior.

For an overall plant balance, refrigeration duty follows changes in stream enthalpy, with relevant heat leaks and side streams included. Compressor power is a separate input and cannot simply be equated with the heat removed from the gas. Module grouping should preserve the process arrangement needed to achieve the specified balance. Extending refrigerant piping to accommodate a convenient module boundary may increase pressure loss or inventory and should trigger reassessment.

Dynamic operability adds another screening layer. Feed interruptions, compressor trips, refrigerant redistribution, and utility failures can move the plant away from steady conditions. The design team should examine how pressure and temperature evolve across module boundaries and whether valves, measurements, and protective actions respond appropriately. A connection that is acceptable during normal flow may behave differently during rapid depressurization or restart. Dynamic simulation is most useful when assumptions about volumes, equipment characteristics, and control response are checked against supplier data. Its purpose is to reveal interactions before physical interfaces become expensive to change, rather than merely reproduce a stable operating point.

5 SELECTING THE MODULAR ARCHITECTURE

Modularization exists on a continuum. At one end, only equipment skids and repeated pipe-rack sections are prefabricated. At the other, large assemblies contain extensive process equipment, piping, instrumentation, and structural steel. Between them, hybrid arrangements combine offsite packages with site-built foundations, major equipment, and interconnections. Selecting among these options requires an explicit definition of what work is transferred and what remains onsite.

The assessment should begin with hard constraints: access dimensions, transport capacity, available lifting equipment, ground bearing conditions, fabrication capability, and supplier package limits. These constraints define feasible module envelopes. Maintenance routes, hazard separation, operational access, and future replacement then determine whether a feasible envelope is also useful. Maximizing module size without these checks can produce assemblies that are difficult to integrate or maintain.

Standardization is related but distinct. A project can modularize unique assemblies without repeating their design, or standardize equipment while constructing it onsite. O'Connor and colleagues distinguish strategies based on standard modules and standardized modular plants [8]. Repetition can simplify interfaces and support learning, but its benefits depend on retaining compatible process duties and site conditions.

A practical architecture therefore separates invariant requirements from adjustable ones. Equipment identification, interface conventions, testing records, and documentation structures may remain consistent. Foundations, cooling

arrangements, insulation details, and structural reinforcement may need local adaptation. Controlled variants are often more credible than a supposedly universal module.

Decision criteria should consider system performance rather than modularization percentage alone. Useful measures include field connection count, inaccessible joints, lifting complexity, transport exposure, rework risk, and commissioning dependencies. A design that moves more labor offsite may still create more difficult final integration. The preferred architecture is the one that provides the most dependable path from engineering definition to an operable plant.

6 MODULE BOUNDARIES AND INTERFACE ENGINEERING

Module boundaries are physical and informational commitments. They define where piping is connected, cables are terminated, structural loads transfer, instruments communicate, and responsibilities change. Boundaries should be selected where these transitions can be controlled and inspected. Drawing an arbitrary rectangle around equipment rarely produces a satisfactory module.

Process interfaces require defined flow, pressure, temperature, composition, allowable pressure loss, and operating cases. Mechanical interfaces require nozzle locations, flange details, tolerances, allowable loads, and access. Structural interfaces need support elevations, anchor arrangements, load paths, and settlement assumptions. Electrical and control interfaces require consistent signal definitions, power requirements, grounding arrangements, and shutdown behavior. Every interface needs an accountable owner on both sides.

A shared interface register should link these requirements to approved drawings and revision status. Changes must be evaluated across the boundary before fabrication proceeds. A revised nozzle orientation, for example, can affect a connecting spool, local platform, instrument location, transport clearance, and installation sequence. Recording only the revised equipment drawing leaves those consequences unresolved.

Some interfaces deserve avoidance where practical. Dividing tightly coupled compressor auxiliaries between distant modules may complicate integration. Locating sensitive cryogenic connections where access is restricted can impair examination and insulation continuity. Conversely, keeping every component within one module can make the assembly too heavy or prevent maintenance. Interface design therefore involves balancing competing requirements, not simply minimizing connection numbers.

Dimensional control must include accumulated tolerances. Fabrication accuracy, survey uncertainty, transport deformation, foundation positioning, and installation movement all affect final fit. Field-fit spools can accommodate measured differences when intentionally designed and controlled; they should not become a substitute for accurate fabrication. Acceptance limits and recovery options need agreement before modules leave the yard.

7 INTEGRATING COMPRESSORS AND CRYOGENIC EXCHANGERS

Refrigerant compressors should be treated as integrated machine systems. The compressor, driver, lubrication system, seals, controls, foundation, and connected piping influence one another. Factory performance testing cannot establish that the installed machine will remain aligned after transport, foundation settlement, or final piping connection. Installation and commissioning requirements must therefore shape module design from the start.

Surge protection is particularly sensitive to system arrangement. Recycle piping volume, valve response, compressor inertia, and pressure dynamics influence transient behavior. Botros, Grose, and Hill present methods for assessing surge-control systems, including detailed dynamic analysis [9]. Their work supports evaluating the connected system rather than approving a valve or controller in isolation. Splitting a compressor system between modules should not invalidate the assumptions used in that analysis.

Cryogenic heat exchangers create different integration demands. Coil-wound and brazed aluminum plate-fin designs have distinct geometries, operating limitations, and support requirements. Plate-fin equipment requires careful attention to cleanliness, fluid compatibility, distribution, and temperature changes. ALPEMA provides specialist guidance addressing these exchangers' manufacture, installation, and operation [10].

Ma and colleagues examine the interaction between manufacturing residual stress and operating stresses in plate-fin structures [11]. Their numerical analysis reinforces the connection between fabrication history and service integrity. For modular plants, this means that exchanger acceptance cannot stop at thermal duty. Transport supports, nozzle loads, preservation, cooldown arrangements, and access for inspection also need agreement with the supplier.

Equipment arrangements should reserve space for realistic maintenance tasks. Compressor internals, motors, filters, valves, and exchanger components require different removal paths. Temporary lifting arrangements may be needed during maintenance, even where installation used a large construction crane. A compact module is technically incomplete if routine access or foreseeable equipment replacement has been omitted.

8 STRUCTURAL DESIGN ACROSS THE MODULE LIFECYCLE

A module structure experiences several distinct support conditions. During fabrication it may rest on temporary stools. During movement it may be supported by transport beams or trailers. During lifting, loads enter through designated lifting points. During operation, permanent foundations support equipment weight, piping reactions, wind, and applicable seismic actions. The governing condition may occur before the plant operates.

The structural model should reflect these stages explicitly. Designers need equipment masses, center-of-gravity locations, stiffness assumptions, temporary supports, lifting geometry, and transport accelerations. Uncertainty in weight distribution can alter reactions and lifting-point loads. A weight-control register should therefore distinguish verified data from estimates and track changes through fabrication. Unrecorded additions can undermine an otherwise adequate analysis.

Consider an illustrative module mass of 1,000 tones subjected to an assumed horizontal acceleration of 0.20 times gravitational acceleration. The simple inertial relationship, force equals mass multiplied by acceleration, gives approximately 1.96 meganewtons. This is not a prescribed design acceleration or a complete load case. It shows why equipment anchorage and temporary restraint require deliberate engineering, even when the module is stationary during normal service.

For waterborne module transport, DNV-ST-N001 addresses marine-operation planning and relevant load cases [12]. Actual design must use the agreed transport configuration, applicable criteria, environmental assumptions, and combinations. The illustrative force above excludes rotational effects, dynamic amplification, support movement, local load distribution, and other actions that may matter.

Strength alone is insufficient. Deflection can damage connected piping or impair final fit without causing structural failure. Vibration can affect sensitive equipment and small-bore attachments. Local stresses at lifting points and temporary supports may govern details that appear minor in the operating model. Temporary conditions deserve the same engineering control as the permanent plant. Required restraints should be identified, installed, inspected, and removed through documented procedures.

9 CRYOGENIC PIPING, MATERIALS, AND INSULATION

Piping design must account for both cryogenic service and module movement. Materials require adequate toughness at the specified minimum temperature, compatibility with the fluid, and suitable fabrication procedures. ASME B31.3 covers process-piping requirements across design, materials, fabrication, examination, and testing [13]. The governing code and edition must be established for the project; modular fabrication does not reduce the applicable integrity requirements.

Thermal contraction can be substantial. As a simplified illustration, assume a straight stainless-steel line is 30 meters long and cools through 180 kelvin. Using an assumed mean expansion coefficient of 16 millionths per kelvin gives a contraction magnitude of approximately 86 millimeters. The coefficient is illustrative: actual calculations require the material's temperature-dependent properties and the relevant temperature range. The result nevertheless explains why rigidly restraining a cold line at both module boundaries can create unacceptable loads.

Stress analysis should include equipment connections, supports, friction, gaps, imposed movements, and relevant operating cases. Transport restraints may be necessary during shipment but incompatible with thermal movement in service. Their removal must be verified before cooldown. The analysis should also consider differential movement between adjacent module foundations and structures.

Interface joints require an intentional connection strategy. Welded connections reduce some potential leak paths but need access for fit-up, welding, examination, and testing. Flanged connections support certain maintenance needs but require suitable gasket, bolt, assembly, and inspection practices. The appropriate choice depends on service and approved design requirements.

Insulation continuity is easily lost at module boundaries. Vapor barriers, weather protection, penetrations, and supports need coordinated details. Field closures should remain accessible until required checks are complete. Do not allow a visually finished insulation system to conceal an unverified connection, incorrect support, or incomplete test record.

Small-bore connections need separate attention because local vibration and handling damage may not be apparent in the main piping model. Instrument tubing, valve extensions, drains, and vents should be supported and protected for both shipment and operation. Their inspection should continue after transport restraints and protective covers are removed. Likewise, temporary attachments must not leave unassessed damage on pressure-containing parts or sensitive structural details. Clear fabrication drawings and removal instructions reduce the chance that a temporary construction measure becomes an undocumented permanent condition. These checks are especially valuable where repeated modules multiply the consequences of one overlooked detail.

10 LAYOUT, CONGESTION, AND PROCESS SAFETY

Modularization often encourages compact layouts, but compactness changes the safety problem. Equipment density, structural framing, pipework, and restricted access can influence ventilation, gas accumulation, incident escalation, and emergency response. Tanabe and Miyake specifically examine safety design for onshore modularized LNG liquefaction plants [14]. Their work identifies the need to consider modular layout characteristics rather than assume that conventional arrangements can be compressed without consequence.

Hazard studies should begin while module boundaries remain adjustable. They should consider loss of containment, ignition, cryogenic exposure, blocked flow, loss of utilities, and abnormal operating sequences. Where detailed consequence analysis is necessary, the model should represent the actual geometry and relevant obstructions. Simplified early studies need revisiting as equipment and structural details mature.

The preferred response is to remove or reduce hazards where practical. This may involve changing equipment placement, reducing unnecessary inventory, improving ventilation, separating incompatible activities, or providing clearer escape routes. Detection, isolation, fire protection, and emergency arrangements then address remaining risks. A safeguard should not be used to justify a poor layout without examining alternatives.

Safety instrumented functions also cross module boundaries. A shutdown may require measurements in one package, logic elsewhere, and final elements in several modules. IEC 61511 addresses the lifecycle of safety instrumented systems [15]. Functional requirements, independence where required, response times, testing arrangements, and failure behavior must remain coherent across package suppliers.

Maintainability is part of safety. Operators should reach isolation points, inspect equipment, and evacuate without navigating avoidable obstructions. Access reviews should consider protective clothing, tools, temporary scaffolding, and simultaneous maintenance. Module reviews become more useful when teams walk through actual tasks instead of checking clearances only against generic drawing notes.

11 ELECTRICAL, CONTROL, AND UTILITY INTEGRATION

Electrical modularization can move assembly and testing into controlled environments, but the installed system still depends on coordinated protection, grounding, cable routing, and power quality. Large compressor drives may affect motor starting, voltage stability, harmonics, and recovery after disturbances. Studies must represent the complete electrical network, including relevant temporary commissioning configurations.

Control integration requires consistent equipment tags, signal ranges, alarm priorities, communication definitions, and cause-and-effect requirements. Package testing should verify agreed behavior, not merely demonstrate that individual instruments produce signals. Loss of communication, sensor failure, power interruption, and restart conditions should be addressed explicitly. Network connections should not create uncontrolled access between supplier systems and plant controls; NIST's operational-technology guidance provides a relevant security framework [16].

Utilities must be evaluated by operating scenario. Instrument air, nitrogen, cooling, heating, and electrical supplies have different startup and emergency demands. Duplicate equipment does not provide effective redundancy if both units share the same vulnerable supply or controller. Module boundaries should preserve access to maintenance isolation and avoid hidden common dependencies. System reviews should establish what the plant does when each essential utility becomes unavailable.

12 FABRICATION QUALITY AND PRESERVATION

Fabrication quality begins with approved information, documents, and traceable materials. Structural steel, pressure-containing components, welding consumables, valves, and instruments need identification appropriate to their service. Inspection and test plans should define acceptance criteria, responsibilities, and hold points before work starts. API RP 582 provides relevant welding guidance for chemical, oil, and gas applications [17], while project codes and specifications establish the binding requirements.

Modular fabrication can improve access and consistency, but it also makes defects easier to repeat. An incorrect detail copied across several assemblies can become a systematic problem. First-article inspections, controlled standard details, and prompt feedback from inspection are therefore important. Repetition should follow verified workmanship rather than proceed solely to maintain fabrication output.

Chi and colleagues propose a framework connecting sensing, tracking, and construction information for LNG module fabrication, delivery, and installation [18]. Their study supports better visibility of deviations across these stages, while its conceptual and preliminary character limits claims about universal performance improvement. Digital records are useful when they connect the physical component to its approved requirements and verified condition.

Preservation extends from factory completion to startup. Moisture, dust, corrosion, vibration, and damaged seals can degrade equipment during storage or movement. Requirements should follow supplier instructions and change as equipment passes from warehouse storage to installed standby. Responsibility must remain clear during every transfer. A module should be released with evidence of quality and preservation, not simply a declaration that fabrication is finished.

Documentation should make these decisions recoverable. A useful module dossier links equipment identifiers to material records, weld examinations, dimensional surveys, calibration results, test boundaries, preservation actions, and accepted deviations. Missing evidence should be treated as an unresolved condition rather than assumed compliance. The format should support transfer between organizations without losing revision history or component identity. Consistent records are particularly important when adjacent modules come from different yards, because the site team must establish compatibility using evidence collected under separate fabrication programs.

13 TRANSPORT, LIFTING, AND INSTALLATION

Transport engineering should start before module dimensions are frozen. Route assessment must consider clearances, turning geometry, grades, ground bearing, temporary crossings, and access to the final foundation. Waterborne movement adds support, restraint, environmental, and handling requirements. The scope here is movement of plant modules during construction, not transport of LNG as a product.

Lifting studies require verified weights, centers of gravity, lifting-point capacities, rigging arrangements, crane configurations, and ground conditions. Clearance throughout the movement matters as much as clearance at the final position. Taghaddos, Hermann, and Abbasi investigate automated crane planning for modular construction [19]. Such methods can support planning, but their output depends on accurate geometry, equipment data, and realistic site constraints.

Installation sequence affects feasibility. An early module may obstruct a later lift, block temporary access, or prevent final piping installation. Construction simulation can reveal these conflicts when it includes temporary works and equipment, not just permanent assemblies. Survey checks should verify foundations and interfaces before the module arrives, while contingency plans should address discrepancies without improvising structural modifications.

After placement, installation records should confirm orientation, support conditions, anchor completion, alignment, and transport-restraint status. Receiving inspection should identify damage or loss of preservation. Shipment acceptance and operational acceptance are different milestones. A module that arrived intact still needs verified connections, completed testing, and integration with the systems around it.

14 EXECUTION PLANNING AND SYSTEM COMPLETION

Modular execution changes the sequence of engineering information. Fabrication yards require sufficiently mature drawings and supplier data earlier than many site-built activities. O'Connor and colleagues examine execution-planning differences between modular and conventional industrial projects [3]. The practical implication is to plan backward from fabrication and installation needs rather than treat modularization as an additional procurement package.

Work packaging can connect drawings, materials, access, tools, supervision, and inspection requirements. Porwal and colleagues report an association between advanced work packaging, workplace planning, and higher direct-work rates across construction datasets [20]. This is useful evidence, but direct-work rate is not identical to installed quality or total project performance. Project teams should also monitor rework, unresolved constraints, and readiness of complete systems.

A particular challenge is the difference between module completion and system completion. A module can be mechanically complete while the utility or control system it depends on remains incomplete elsewhere. Progress reporting should therefore retain both views: physical assembly status and operational system status. Otherwise, impressive fabrication percentages may obscure the actual path to startup.

Changes require coordinated impact assessment. Revised process duties, instrument connections, or support details may affect several yards and the site simultaneously. A controlled change process should identify affected modules, drawings, procurement items, tests, and installation activities. Closing the engineering revision is insufficient until the corresponding physical work and completion records have also been reconciled.

15 TESTING, COMMISSIONING, AND HANDOVER

Testing should demonstrate integrity and function through a planned sequence. Factory tests can verify equipment and package behavior within defined boundaries. Site tests address installation, interconnections, integrated controls, and conditions that could not be reproduced before shipment. Neither stage should be assumed to replace the other automatically. Acceptance criteria and test responsibilities should be agreed before fabrication release.

Pressure testing requires particular care because of stored energy. HSE's GS4 guidance addresses the hazards and management of these activities [21]. The approved method must suit the equipment, materials, and circumstances. Test completion should be followed by controlled reinstatement and, where required, drying and preservation. A passed pressure test does not establish cleanliness or readiness for cryogenic operation.

Commissioning should proceed by operating systems. O'Connor, Leite, and Ma propose extending advanced work packaging into commissioning and startup through systems-oriented packages [22]. This approach helps connect distributed construction activities with the dependencies needed to operate equipment. Utilities, controls, protective functions, and process equipment must reach compatible states before the next commissioning stage begins.

Before cooldown, teams should verify cleanliness, required dryness, support arrangements, instrument availability, approved procedures, and removal of incompatible temporary restraints. Temperature changes and observations should follow supplier and project limits. Unexpected movement, unstable readings, or unexplained pressure behavior require assessment rather than schedule-driven continuation.

Handover includes accurate as-built information, maintenance requirements, spare parts, training, and outstanding-item ownership. Performance testing should use agreed reference conditions and methods. Operational readiness is demonstrated by complete, usable systems and competent personnel, not by the number of modules installed.

16 ENGINEERING VERIFICATION AND DECISION GATES

Verification should be organized around decisions that become difficult to reverse. Before module boundaries are approved, the team should confirm process compatibility, equipment access, feasible transport envelopes, and preliminary safety requirements. Before fabrication release, the principal interfaces, structural assumptions, supplier connections, and inspection requirements should be sufficiently mature. Before shipment, dimensional acceptance, preservation, lifting arrangements, temporary restraints, and unresolved deviations require documented disposition.

These gates should evaluate evidence, not document counts. An issued drawing may still contain assumptions that affect another discipline. A completed test may exclude the connection that matters for system integration. Reviewers therefore need to ask whether the required function has been demonstrated under the relevant conditions, and whether remaining uncertainty has an owner and an acceptable resolution path.

Reliability reviews should examine shared dependencies as well as individual package availability. Several repeated modules can remain vulnerable to one electrical bus, common cooling source, control network, or maintenance isolation error. The ability to operate one module independently should be demonstrated through process and utility arrangements, rather than inferred from physical separation. Where independence is unnecessary, the shared dependency should still be understood and reflected in operating procedures.

A useful final check compares the approved design with the installed configuration. Survey results, field changes, supplier revisions, and commissioning modifications should be reconciled before handover. This closes the gap between a coordinated model and a coordinated plant. Without that reconciliation, later operators may inherit accurate-looking documents that describe an arrangement no longer present onsite.

17 GLOBAL APPLICATION AND RESEARCH PRIORITIES

Global execution requires consistent technical expectations with controlled local adaptation. Hot environments can affect cooling capacity and driver performance. Humid locations demand careful corrosion protection, drainage, and preservation. Cold regions may require winterization and evaluation of frozen-ground behavior. Seismic regions require compatible structural, piping, and equipment responses. Remote locations increase the importance of maintainability, spares, and realistic technical support.

Fabrication capability also varies. A yard's experience with structural assemblies does not automatically establish competence in cryogenic piping, cleanliness control, instrumentation, or integrated package testing. Qualification should examine the actual work scope. Language differences, inspection practices, measurement conventions, and document systems require deliberate coordination across participating organizations.

The literature leaves several important research needs. Published process optimization often has limited representation of transport, construction sequence, maintenance access, and commissioning effort. Conversely, modularization studies may simplify process interactions. Better integrated models could evaluate thermodynamic performance alongside physical interfaces and lifecycle constraints. Such models need validation against project and operating evidence, not only internally consistent simulations.

Further work should examine how measured fabrication accuracy, transport exposure, field rework, and commissioning outcomes are related. Comparable definitions and transparent boundaries would make studies more useful. Digital tools can help collect this evidence, but trustworthy results still depend on disciplined tagging, measurement, and reporting.

Performance measures should also distinguish the amount of offsite work from its effectiveness. Module count is a weak indicator because assemblies vary greatly in size and complexity. Reporting should define whether modularization is measured by transferred labor, installed equipment, fabrication scope, or another consistent basis. Comparisons then need equivalent boundaries and clear treatment of site interconnections. This prevents an apparently higher degree of modularization from masking increased field work, delayed system integration, or repeated corrective activities after delivery and installation.

18 CONCLUSIONS

LNG plant design and modularization are interconnected engineering decisions. Refrigeration selection determines equipment duties and geometry; module architecture changes interfaces, transport conditions, and installation sequence; and those choices influence integrity, safety, and operational readiness. Treating modularization as a late construction decision leaves important dependencies unresolved.

The strongest practices are consistent across locations: establish a common design basis, define feasible module envelopes early, control interfaces, verify equipment information, analyze temporary load cases, preserve cryogenic integrity, and plan completion around operating systems. Standardization supports repetition only when its applicability is checked. Digital models and automated planning strengthen coordination when they reflect verified physical conditions.

The reviewed literature supports integrated decision-making but does not justify universal claims about the best module size or guaranteed performance gains. Each project must demonstrate that its chosen arrangement is transportable, constructible, maintainable, and safe. A successful modular LNG plant is ultimately judged by the integrity and dependability of the complete facility after all assemblies have been connected and commissioned.

STATEMENTS ON COMPLIANCE WITH ETHICAL STANDARDS

Disclosure of conflict of interest

The authors declare no conflicts of interest regarding this manuscript

REFERENCES

- [1] Lim, W., Choi, K., and Moon, I. (2013). Current Status and Perspectives of Liquefied Natural Gas (LNG) Plant Design. *Industrial & Engineering Chemistry Research*, 52(9), 3065–3088.
- [2] O'Connor, J. T., O'Brien, W. J., and Choi, J. O. (2014). Critical Success Factors and Enablers for Optimum and Maximum Industrial Modularization. *Journal of Construction Engineering and Management*, 140(6), 04014012.
- [3] O'Connor, J. T., O'Brien, W. J., and Choi, J. O. (2016). Industrial Project Execution Planning: Modularization versus Stick-Built. *Practice Periodical on Structural Design and Construction*, 21(1), 04015014.
- [4] Santos, M. G. R. S., Correia, L. M. S., de Medeiros, J. L., and Araújo, O. Q. F. (2017). Natural gas dehydration by molecular sieve in offshore plants: Impact of increasing carbon dioxide content. *Energy Conversion and Management*, 149, 760–773.
- [5] Zhang, J., Meerman, H., Benders, R., and Faaij, A. (2020). Comprehensive review of current natural gas liquefaction processes on technical and economic performance. *Applied Thermal Engineering*, 166, 114736. Technical comparisons cited.
- [6] Watson, H. A. J., Vikse, M., Gundersen, T., and Barton, P. I. (2018). Optimization of single mixed-refrigerant natural gas liquefaction processes described by nondifferentiable models. *Energy*, 150, 860–876.
- [7] Wu, X., Wang, Z., Dai, X., Ge, Q., and Liu, F. (2021). Optimization Design and Analysis of Single-Stage Mixed Refrigerant Liquefaction Process. *Frontiers in Energy Research*, 9, 766588.
- [8] O'Connor, J. T., O'Brien, W. J., and Choi, J. O. (2015). Standardization Strategy for Modular Industrial Plants. *Journal of Construction Engineering and Management*, 141(9), 04015026.
- [9] Botros, K., Grose, J., and Hill, S. (2015). A New Approach to Designing Centrifugal Compressor Surge Control Systems. *Proceedings of the 44th Turbomachinery Symposium*. Texas A&M Engineering Experiment Station.
- [10] ALPEMA. Standards of the Braze Aluminium Plate-Fin Heat Exchanger Manufacturers' Association. Standards overview.
- [11] Ma, H., et al. (2021). The influence of residual stress for the strength of plate-fin structures in the typical operation process of Liquefied Natural Gas (LNG) heat exchanger. *Oil & Gas Science and Technology*, 76, 76.
- [12] DNV. (2023). DNV-ST-N001: Marine Operations and Marine Warranty. Edition 2023-12; public scope statement (<https://www.dnv.com/energy/standards-guidelines/dnv-st-n001-marine-operations-and-marine-warranty/>).
- [13] American Society of Mechanical Engineers. ASME B31.3: Process Piping. Official code scope; project-adopted edition to be confirmed (<https://www.asme.org/codes-standards/find-codes-standards/b313-2018-process-piping>).
- [14] Tanabe, M., and Miyake, A. (2010). Safety design approach for onshore modularized LNG liquefaction plant. *Journal of Loss Prevention in the Process Industries*, 23(4), 507–514.
- [15] International Electrotechnical Commission. (2016). IEC 61511-1: Functional Safety—Safety Instrumented Systems for the Process Industry Sector (<https://webstore.iec.ch/en/publication/24241>).
- [16] National Institute of Standards and Technology. (2023). Guide to Operational Technology (OT) Security. NIST SP 800-82, Revision 3 (<https://csrc.nist.gov/pubs/sp/800/82/r3/final>).
- [17] American Petroleum Institute. (2023). API RP 582: Welding Guidelines for the Chemical, Oil, and Gas Industries, fourth edition. Publication record (<https://www.apiwebstore.org/standards/582>).
- [18] Chi, H.-L., Wang, J., Wang, X., Truijens, M., and Yung, P. (2015). A Conceptual Framework of Quality-Assured Fabrication, Delivery and Installation Processes for Liquefied Natural Gas (LNG) Plant Construction. *Journal of Intelligent & Robotic Systems*, 79, 433–448.
- [19] Taghaddos, H., Hermann, U., and Abbasi, A. B. (2018). Automated Crane Planning and Optimization for modular construction. *Automation in Construction*, 95, 219–232.
- [20] Porwal, V., et al. (2025). Examining the impact of Advanced Work Packaging and WorkFace planning on direct work rates of on-site construction workers: a comparative analysis. *Frontiers in Built Environment*, 11, 1621337.
- [21] Health and Safety Executive. Safety Requirements for Pressure Testing. Guidance Note GS4 (<https://www.hse.gov.uk/pubns/gs4.htm>).
- [22] O'Connor, J. T., Leite, F., and Ma, J. W. (2023). Expanding advanced work packaging to include commissioning and startup for industrial projects. *Construction Innovation*, 23(5), 939–960.