

Advanced Flexibility Analysis and Nozzle Load Optimization for Critical Pipelines Connected to Compressors, Pumps, and Pressure Vessels

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Abstract- Critical piping attached to compressors, pumps and pressure vessels occupies a narrow design space in which flexibility must be sufficient to protect equipment nozzles, but stiffness must remain adequate for vibration control, alignment, maintainability and pressure containment. Recent literature has expanded the analytical basis for this problem through refined finite-element modelling, updated piping and machinery standards, digital monitoring and optimisation-based support design. This review synthesises scholarship and authoritative engineering sources published between 2020 and 2025 to clarify how advanced flexibility analysis and nozzle-load optimisation are being reframed for safety-critical industrial piping. The review used a transparent source-search and thematic synthesis process covering scholarly databases, standards repositories and specialist engineering literature. The synthesis identifies four dominant themes: load-path modelling at equipment interfaces, stress classification and local shell behaviour, support and routing optimisation, and the emergence of data-informed integrity management. The evidence shows strong convergence around the need to treat nozzle loads as coupled structural, thermal, hydraulic and operational phenomena rather than as isolated compliance checks. However, the literature remains fragmented across piping stress analysis, pressure-vessel design, rotating-equipment installation and digital integrity research. Persistent gaps include limited validation under transient thermal and dynamic loads, sparse treatment of multi-equipment systems, inconsistent representation of support friction and poor integration between design-stage optimisation and operational monitoring. The review proposes future work on benchmarked digital twins, uncertainty-aware optimisation, life-cycle nozzle-load governance and machine-readable acceptance criteria. Its contribution is an integrated conceptual basis for more resilient, verifiable and adaptable piping systems connected to critical equipment.

Keywords: *Piping Flexibility Analysis, Nozzle Loads, Compressor Piping, Pump Piping, Pressure-Vessel Nozzles, Support Optimisation, Digital Integrity.*

I. INTRODUCTION

Piping attached to compressors, pumps and pressure vessels provides mechanical continuity between process equipment, but it also transmits expansion forces, sustained weight, pressure thrust, vibration, settlement and occasional loads into equipment interfaces. In critical services, the acceptability of a piping layout is therefore determined not only by pipe stress ratios, but also by the force and moment envelope imposed on each nozzle. Contemporary process piping codes emphasise the control of sustained, displacement and occasional stress, while machinery standards place explicit limits on the external loads that may be imposed on rotating equipment casings (American Society of Mechanical Engineers, 2024a; American Petroleum Institute, 2021, 2022, 2024a). Pressure-vessel rules similarly require local shell behaviour around openings to be assessed with adequate regard for reinforcement, plastic collapse and fatigue mechanisms (American Society of Mechanical Engineers, 2025). These requirements make flexibility analysis a shared problem across piping, machinery and vessel disciplines.

The term critical pipeline is used here to denote piping whose failure would have significant safety, environmental, production or equipment-damage consequences. Such piping is normally associated with high pressure, high temperature, low temperature, cyclic duty, hazardous fluids, large rotating equipment or pressure-boundary discontinuities. In these systems, a nozzle is not merely a connection detail; it is a structural interface where discipline assumptions meet. Piping engineers may regard it as a boundary condition, machinery engineers as a casing limitation, and vessel engineers as a reinforced opening. This divided ownership can

obscure the cumulative effect of load combinations and field modifications.

The research problem addressed in this review is the persistent difficulty of optimising nozzle loads without compromising system reliability. A piping route that is highly flexible may satisfy thermal expansion requirements, yet amplify vibration, increase support complexity, promote poor drainage or reduce constructability. Conversely, a stiff route may ease alignment and vibration control but transfer excessive moments to pump, compressor or vessel nozzles. Recent studies of pump piping, compressor piping and marine process systems show that thermal movement, hull deformation, support position and operating pressure can substantially alter nozzle reactions and local stresses (Hwang et al., 2020; Jha et al., 2021; Wang et al., 2022; Yeo et al., 2023). The optimisation problem is therefore multi-objective, constrained by code compliance, equipment vendor limits, operating envelopes, fabrication tolerances and life-cycle inspection needs.

A review is needed now for three reasons. First, the relevant knowledge is distributed across separate domains: piping stress analysis, pressure-vessel nozzle assessment, rotating-equipment installation, vibration control, pipe routing and digital monitoring. Second, recent standards and studies increasingly support risk-based and performance-informed decisions, but they do not provide a unified methodology for balancing flexibility, nozzle protection and dynamic integrity. Third, digital twins and machine-learning methods are entering pipeline and piping integrity management, creating opportunities to connect design assumptions with operating evidence (Rachman et al., 2021; Sandhu et al., 2024; Wang et al., 2024; Chen et al., 2025).

The aim of this review is to synthesise recent knowledge on advanced flexibility analysis and nozzle-load optimisation for critical pipelines connected to compressors, pumps and pressure vessels. Its objectives are to define the main analytical concepts, compare recent modelling and optimisation approaches, identify unresolved technical and methodological gaps, and propose future directions for research and practice. The

manuscript proceeds by describing the review methodology, establishing the conceptual background, synthesising the literature thematically, critically discussing gaps, proposing future research, outlining implications and concluding with the contribution of the review.

II. REVIEW METHODOLOGY

The review followed a transparent narrative synthesis design suitable for a technically heterogeneous field. Searches were conducted for literature published from January 2020 to August 2025. Source types included peer-reviewed journal articles, conference papers indexed in scholarly databases, recent review articles, and current editions or reaffirmations of engineering standards that are directly used in piping, machinery and pressure-vessel design. The search covered engineering databases and publisher platforms using combinations of the terms pipe stress, piping flexibility, nozzle loads, pump piping, compressor piping, pressure-vessel nozzle, support optimisation, vibration, digital twin and pipeline integrity. Standards were included where they governed external equipment loads, stress evaluation, installation, pulsation control or pressure-vessel design.

Inclusion criteria required each source to address at least one of four issues: flexibility or stress analysis of piping systems, nozzle or vessel-opening behaviour, equipment-interface loads for pumps or compressors, or optimisation and monitoring methods relevant to piping integrity. Sources had to be published or reaffirmed between 2020 and 2025 and written in English. Exclusion criteria removed papers concerned only with internal fluid performance, general plant layout without mechanical load analysis, corrosion-only inspection without structural relevance, or empirical studies whose data could not be linked to piping flexibility, support design or nozzle integrity. Older foundational concepts were not cited as references because the review deliberately concentrates on recent literature and standards.

Screening proceeded in three stages. Titles and abstracts were first checked for relevance to critical

piping or equipment nozzles. Full texts were then reviewed to determine whether the technical content concerned load transfer, stress categorisation, support placement, dynamic effects, fatigue, routing optimisation or monitoring. Finally, sources were organised into thematic groups corresponding to design codes and acceptance criteria, nozzle-local structural response, rotating-equipment piping, support and routing optimisation, vibration and pulsation, and digital integrity. The synthesis compared the assumptions, modelling strategies, outputs and limitations reported across these groups. During synthesis, extracted information was recorded under six headings: equipment type, load mechanism, modelling approach, acceptance criterion, optimisation variable and stated limitation. This structure allowed unlike studies to be compared without forcing them into a single metric. For example, a paper on vessel-nozzle stress linearisation and a paper on pump piping flexibility were compared through the shared question of how global loads are translated into local acceptance decisions. Where sources disagreed, the review examined whether the difference arose from service context, boundary conditions, element choice, or the level of conservatism embedded in the governing criterion.

Because this is a review paper, no new field measurements, experimental campaigns or numerical case studies were created. Analytical claims are derived from the reviewed sources and from logical comparison of their stated methods. The synthesis gives greater interpretive weight to studies that provide explicit modelling assumptions, validation or connection to engineering acceptance criteria. Standards are treated as normative sources rather than research findings, while peer-reviewed studies are used to evaluate where practice is well supported or remains uncertain. This approach enables a disciplined comparison of evidence without presenting the review as an empirical investigation.

III. CONCEPTUAL AND THEORETICAL BACKGROUND

Flexibility analysis evaluates whether a piping system can absorb thermal expansion, imposed displacements and mechanical loading without

overstressing the pipe or overloading connected equipment. In critical services, its theoretical basis combines beam behaviour, pressure-boundary mechanics, structural dynamics, local shell theory and fatigue assessment. The pipe span, bend, reducer, valve and support arrangement form a load path whose stiffness distribution determines how displacement is transformed into forces and moments. The nozzle is a discontinuity within this load path. It couples global pipe reactions to local shell deformation in vessels, casing distortion in pumps and compressors, flange leakage risk, shaft misalignment and bearing loads.

The underlying mechanics can be expressed as a compatibility problem. Thermal expansion creates free movement; restraints convert some of that movement into reactions; equipment nozzles receive the portion not absorbed by bends, offsets, supports or flexible elements. Pressure contributes longitudinal stress and, in certain configurations, unbalanced thrust. Dynamic excitation adds inertia and damping dependence. Fatigue then connects stress range, cycle count and local concentration. The theory is straightforward in abstraction, but plant layouts make it difficult because real boundary conditions are semi-rigid, non-linear and history-dependent.

Three analytical distinctions are central. The first separates code stress from equipment load. A line may satisfy process-piping stress limits while still exceeding nozzle allowables supplied by machinery standards or equipment manufacturers (American Petroleum Institute, 2021, 2022; American Society of Mechanical Engineers, 2024a). The second separates global flexibility from local flexibility. Nozzle-shell intersections may experience local membrane and bending stresses that are not visible in a global beam model, particularly when pressure, external moments and reinforcement details interact (Abdalla, 2021; Bozkurt et al., 2021; Bozkurt et al., 2023a). The third separates static compliance from dynamic robustness. Piping that is acceptable under sustained and thermal expansion cases can still be vulnerable to acoustic pulsation, flow-induced vibration or machinery excitation, especially near positive-displacement

machinery (American Petroleum Institute, 2024b; Wang et al., 2022).

Recent literature shows an evolution from deterministic code checking toward integrated flexibility governance. Conventional design practice relies on piping analysis software, spring supports, expansion loops, anchors, restraints and equipment-load comparisons. More recent work extends this logic through finite-element stress linearisation at nozzles, friction-aware support optimisation, route optimisation and monitoring-oriented digital models (Bozkurt and Nash, 2023b; Lee et al., 2024; Utomo et al., 2024; Chen et al., 2025). The conceptual direction is not a rejection of code-based design, but an expansion of the design boundary. Flexibility is increasingly treated as a system property that must be demonstrated across design, installation, commissioning and operation.

For compressors, pumps and vessels, nozzle-load optimisation is best understood as constrained redistribution. The designer cannot eliminate loads; loads are redistributed between pipe stresses, support reactions, equipment nozzles, restraints and flexible elements. Theoretical adequacy therefore depends on matching the model to the dominant mechanism. Thermal expansion demands displacement-based flexibility. Heavy valves and vertical risers demand sustained-load support. Compressor pulsation demands dynamic stiffness and acoustic separation. Vessel nozzles demand local shell verification. This layered view underpins the framework proposed in Figure 1.

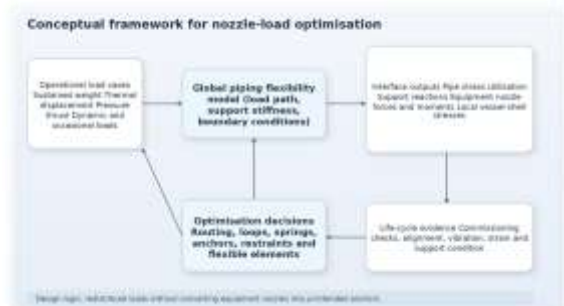


Figure 1. Conceptual framework for flexibility-controlled nozzle-load optimisation in critical equipment-connected piping.

Editable diagram description: Recreate as a left-to-right flow of rounded rectangles for operational load cases, global piping model, interface outputs, optimisation decisions and life-cycle evidence, with thin arrows showing feedback from evidence and decisions to the model. Use a pale blue-grey gradient background, white cards, subtle shadows and small sans-serif labels.

IV. THEMATIC REVIEW AND SYNTHESIS

4.1 Code-based flexibility and equipment acceptance criteria

Current standards provide the baseline for engineering judgement. Process piping rules define stress categories and examination expectations for metallic piping systems, while power-piping rules give corresponding requirements for services such as steam and high-energy utility lines (American Society of Mechanical Engineers, 2024a, 2024b). Equipment standards specify external nozzle-load expectations for centrifugal pumps, centrifugal and axial compressors, and reciprocating compressors (American Petroleum Institute, 2021, 2022, 2024a). Machinery installation guidance further links piping flexibility to grouting, alignment, baseplate design and field fit-up (American Petroleum Institute, 2024c). These documents converge on a practical message: equipment nozzles should not become unintended anchors.

Yet code compliance does not equal optimisation. Codes typically define minimum acceptability, whereas nozzle-load optimisation seeks a load distribution that remains stable across operating modes, transient conditions and installation tolerances. Aswin and Hasnan (2023) show that support type and location can materially influence stress in high-pressure steam piping. Jha et al. (2021) similarly demonstrate that pump systems require iterative stress analysis because allowable nozzle reactions, support locations and thermal movements interact. The literature supports a design sequence in which stress limits, equipment load ratios and displacement compatibility are evaluated together, not in separate discipline silos.

4.2 Local nozzle behaviour in pressure vessels

Pressure-vessel nozzles introduce geometric discontinuities that concentrate stress. Recent finite-element studies show that the interaction of internal pressure and external nozzle loads changes collapse behaviour and local stress distribution. Bozkurt et al. (2020) examined how pressure and external forces affect cylindrical vessel nozzles, while Abdalla (2021) generated interaction diagrams for padded and unpadded vessel-nozzle structures using plastic collapse techniques. Bozkurt et al. (2021) compared stress-analysis and limit-analysis approaches for single and multiple nozzle combinations, showing that the selected assessment route can influence the apparent margin. Later work on crotch-corner cracks under internal pressure and nozzle loads linked nozzle loading to fracture-mechanics concerns (Bozkurt et al., 2023a).

Reinforcement geometry remains a key design variable. Bozkurt and Nash (2023b) investigated stress linearisation for oblique nozzles with welded pad reinforcement, and Swit and Szczecina (2025) used numerical modelling to study reinforcing-pad geometry. Romanowicz and Szybinski (2021) and Ma et al. (2024) further illustrate the broader importance of numerical and fatigue methods in pressure-boundary optimisation. Collectively, these studies indicate that global piping models should not be treated as sufficient for vessel-nozzle decisions when high loads, fatigue-sensitive service, oblique intersections or multiple openings are present. A defensible workflow links the piping model to local vessel assessment through transferred load components, load combinations and sensitivity checks.

4.3 Rotating-equipment piping: pumps and compressors

Pumps and compressors differ from vessels because nozzle loads affect both pressure containment and machine performance. Excessive external reactions may distort casings, disturb internal clearances, alter shaft alignment or increase bearing loads. Pump piping is especially sensitive to thermal growth, suction-side pressure losses, poor anchoring and field misalignment. API pump requirements and installation practices emphasise that piping should be

independently supported and aligned without forcing the equipment into position (American Petroleum Institute, 2021, 2024c). Jha et al. (2021) confirm that pump piping assessment must incorporate operating temperature, nozzle allowables and support reaction management.

Compressor piping adds stronger dynamic complexity. Centrifugal compressor systems require attention to casing loads, nozzle loads, thermal movements and acoustic interactions, while reciprocating compressor systems require pulsation and vibration control as integral design tasks (American Petroleum Institute, 2022, 2024a, 2024b). Wang et al. (2022) analysed pressure pulsation and stress in a low-temperature compressor piping system and showed that pulsation can be structurally significant when combined with thermal and mechanical effects. This evidence supports treating compressor nozzle optimisation as a combined static-dynamic problem. A layout that only minimises static nozzle moments may inadvertently place supports or spans in configurations that amplify vibration.

4.4 Support, restraint and routing optimisation

Support design is the main practical means of controlling flexibility and nozzle loads. The reviewed studies show a shift from manual trial-and-error toward explicit optimisation. Yeo et al. (2023) proposed optimal support arrangement considering safety and production cost, and Lee et al. (2024) developed a method for locating friction supports to attenuate vibrational energy. These studies are important because friction supports are often simplified in conventional models even though their stick-slip behaviour can change thermal reactions and dynamic response. Aswin and Hasnan (2023) also show that support type, not only support spacing, affects stress outcomes.

Routing optimisation extends the same principle to the layout level. Utomo et al. (2024) used global optimisation for ship engine-room pipe arrangements, and Markhorst et al. (2025) developed uncertainty-aware pipe-routing optimisation for future design conditions. Such approaches are transferable to process plants, but nozzle loads must be included as explicit objectives rather than checked only after an

optimal route is selected. If route length, clashes and cost dominate optimisation, the resulting design may still require compensatory loops, springs or expansion joints. The emerging best practice is simultaneous optimisation: route, support, flexibility and equipment-interface criteria should be considered in one decision space.

4.5 Monitoring, digital twins and life-cycle integrity

Recent digital integrity research provides a path for closing the gap between design assumptions and operating behaviour. Reviews of machine learning for pipeline integrity show that data-driven methods can classify degradation, forecast risk and support decision-making, but they require transparent features and credible physical context (Rachman et al., 2021; Hussain et al., 2024). Sandhu et al. (2024) compared deep-learning models for condition monitoring of advanced reactor piping, while Wang et al. (2024) presented a pipeline condition-monitoring case directed toward a digital twin. Chen et al. (2025) proposed a digital-twin-based predictive diagnosis approach for suspended submarine pipelines. Although these studies are not all concerned with equipment nozzles, they provide methods that could be adapted to monitor displacement, strain, vibration and support condition in critical piping.

The evidence suggests that nozzle-load optimisation should not end at design approval. Installation tolerances, support gaps, settlement, insulation weight, operating cycles and maintenance interventions can invalidate initial assumptions. A life-cycle approach would preserve the design load envelope, compare it with commissioning measurements, and update the model when field evidence indicates changed boundary conditions. This is particularly relevant for critical compressor and pump systems, where alignment, vibration and thermal growth are repeatedly altered by maintenance activities.

4.6 Fatigue, fabrication and constructability considerations

Nozzle-load optimisation also depends on fatigue and fabrication realism. Work on flat-end head geometries and reactor pressure-vessel fatigue

confirms that local pressure-boundary details may require both numerical and fatigue-oriented assessment when cyclic duty is significant (Romanowicz and Szybinski, 2021; Ma et al., 2024; Yuan et al., 2025). These studies reinforce a broader point: a nozzle-load solution that passes a static code case may still be inadequate when weld detail, reinforcement geometry, thermal cycles and inspection access are considered together.

Constructability is similarly underdeveloped in formal optimisation. Spring hangers may be theoretically effective but difficult to commission; expansion joints may reduce nozzle loads but introduce maintenance and pressure-thrust concerns; rigid struts may stabilise vibration but increase thermal reactions. Field cutting, fit-up, cold pull and temporary construction supports can alter the load path before operation begins. Installation guidance recognises the need to avoid forcing piping into position, yet academic optimisation studies seldom model these construction states (American Petroleum Institute, 2024c). A mature design method should therefore evaluate not only the final hot operating case, but also hydrotest, cleaning, shipping, erection, first heat-up and maintenance disassembly.

4.7 Integrated synthesis

Across the themes, the most consistent finding is that nozzle loads are emergent rather than local. They arise from routing, support stiffness, thermal gradients, pressure, vibration, equipment growth and local shell flexibility. The reviewed literature does not support a universal preference for loops, springs, anchors or expansion joints. Instead, it supports mechanism-specific design: remove thermal displacement from sensitive nozzles, restrain dynamic spans where needed, verify local vessel discontinuities explicitly, and preserve field alignment. The practical challenge is sequencing. Decisions made during plot planning and three-dimensional routing often determine whether later stress optimisation is easy or impossible. Early integration is therefore more effective than late correction.

The synthesis in Table 1 condenses the principal themes and their relevance to the review objectives.

Table 1. Structured summary of key themes, representative findings, cited sources and relevance to the review objectives.

Theme	Representative findings	Cited sources	Relevance to review objectives
Code and equipment criteria	Piping stress compliance and equipment nozzle allowables must be assessed together; standards provide minimum acceptability rather than optimisation.	American Society of Mechanical Engineers (2024a, 2024b, 2025); American Petroleum Institute (2021, 2022, 2024a, 2024b, 2024c)	Defines governing constraints and clarifies why nozzle loads are interface design outputs.
Local vessel-nozzle mechanics	External loads, internal pressure, reinforcement geometry and crack location interact in local stress, collapse and fatigue behaviour.	Abdalla (2021); Bozkurt et al. (2020, 2021, 2023a); Bozkurt and Nash (2023b); Swit and Szczecina (2025)	Shows why beam-based piping reactions must be coupled to local pressure-boundary assessment.
Rotating-equipment piping	Pump and compressor nozzles are affected by thermal growth, casing distortion, pulsation, alignment	Jha et al. (2021); Wang et al. (2022); American Petroleum Institute	Connects flexibility analysis with machinery protection and dynamic integrity.

	and support reactions.	(2021, 2022, 2024a)	
Support and routing optimisation	Support type, friction, routing and cost can be formulated as optimisation variables but nozzle loads must be explicit objectives.	Aswin and Hasnan (2023); Yeo et al. (2023); Lee et al. (2024); Utomo et al. (2024); Markhorst et al. (2025)	Identifies practical levers for redistributing load without reducing constructability.
Digital and life-cycle integrity	Monitoring, machine learning and digital twins can compare operating behaviour with design assumptions when physical mechanisms are retained.	Rachman et al. (2021); Hussain et al. (2024); Sandhu et al. (2024); Wang et al. (2024); Chen et al. (2025)	Frames future flexibility management as an auditable life-cycle process.

V. CRITICAL DISCUSSION

The recent literature provides strong analytical tools but remains unevenly integrated. Its main strength is the improvement of local and system-level modelling. Finite-element work on vessel nozzles has clarified how external loads, pressure, reinforcement and crack geometry influence local stress and collapse margins (Abdalla, 2021; Bozkurt et al., 2021; Bozkurt et al., 2023a; Swit and Szczecina, 2025). Support-optimisation studies show that safety and cost can be formulated as explicit design objectives rather than treated as informal judgement (Yeo et al., 2023; Lee et al., 2024). Digital-integrity research demonstrates that monitoring and predictive

diagnosis can supplement periodic inspection, especially where complex operating environments challenge deterministic models (Sandhu et al., 2024; Chen et al., 2025).

The weaknesses are equally significant. First, many studies optimise only one part of the problem. A vessel-nozzle paper may provide excellent local stress insight without addressing compressor pulsation, while a routing study may reduce layout cost without evaluating vendor nozzle limits. Second, validation remains limited. Numerical models often rely on ideal supports, ideal geometry and deterministic load cases, although real plants contain restraint gaps, cold-spring deviations, settlement, anchor flexibility and friction uncertainty. Third, transient events are underrepresented. Start-up, shutdown, trip, steam-out, chill-down, surge, valve closure and blocked-discharge scenarios can govern nozzle reactions, yet are difficult to represent in steady-state flexibility models.

There is also a conceptual tension between flexibility and restraint. Traditional flexibility solutions add loops, offsets or spring supports, but critical compressor and pump systems often need short, well-restrained spans to control vibration and pulsation. The best solution is rarely maximum flexibility; it is sufficient flexibility located away from equipment, with deliberate stiffness where dynamic integrity requires it. This distinction is not always made explicit in current scholarship.

Another weakness is the limited treatment of documentation as an engineering control. Nozzle-load calculations often produce pass-or-fail reports, but the rationale for selected supports, inactive load cases, assumed friction factors and accepted vendor margins may not be retained in a form usable by operations teams. When a plant is debottlenecked or a pump is replaced, the historical load-path logic may be unavailable. This weakens organisational learning and encourages local modifications that appear harmless but change equipment reactions.

Geographical and sectoral concentration also limits generalisation. Much of the recent work is drawn from process, marine, nuclear and oil-and-gas

contexts, but each sector has different risk tolerances, documentation practices and monitoring maturity. Ethical and policy issues are indirect but real: poor nozzle-load governance can contribute to leaks, unplanned shutdowns and safety incidents. The literature would benefit from stronger links between technical optimisation, asset-management accountability and auditable decision records.

VI. FUTURE RESEARCH DIRECTIONS

Future research should move from isolated compliance checks toward life-cycle optimisation of equipment-interface integrity. First, benchmark models are needed for pump, compressor and vessel-nozzle systems. These benchmarks should include published geometry, boundary conditions, thermal cases, dynamic excitations, nozzle allowables and measured responses. They would allow researchers to compare finite-element, beam-model and reduced-order digital-twin approaches on common problems. Second, uncertainty-aware optimisation should become standard. Support friction, soil or structural settlement, spring variability, restraint gaps and installation misalignment should be represented as uncertain variables rather than hidden safety margins. Such models could identify designs whose nozzle loads remain acceptable across plausible construction and operating variability.

Third, future studies should combine thermal flexibility with dynamic design. Compressor systems in particular require simultaneous assessment of static nozzle reactions, pulsation, mechanical natural frequencies and fatigue. The evidence from pulsation and vibration studies indicates that sequential analysis can miss interactions that are structurally important (American Petroleum Institute, 2024b; Wang et al., 2022).

Fourth, local vessel-nozzle assessment should be more directly coupled to plant piping models. Automated transfer of load combinations from piping analysis to shell finite-element models would reduce transcription errors and enable sensitivity studies for reinforcement thickness, pad geometry and nozzle orientation.

Fifth, monitoring research should target quantities that matter to nozzle governance: hot and cold displacement, pipe strain near anchors, support lift-off, vibration at small-bore connections, and post-maintenance alignment drift. Digital twins will be credible only if their inputs reflect observable mechanisms rather than generic data streams (Rachman et al., 2021; Wang et al., 2024; Chen et al., 2025).

Sixth, future work should develop machine-readable acceptance criteria that link piping-code stress checks, equipment-standard limits and vessel local assessment into auditable workflows. This would support automated design review while preserving engineering judgement. Seventh, research should address constructability explicitly. Optimisation studies should include installation states, temporary restraints, hydrotest loading, spring-setting procedures and commissioning measurements. Eighth, interdisciplinary datasets should be developed so vessel, piping and machinery researchers can evaluate the same interface problem from their respective acceptance criteria. Table 2 translates these priorities into a research-gap matrix.

Table 2. Research-gap and future-direction matrix for nozzle-load optimisation and flexibility analysis.

Identified gap	Evidence limitation	Implications	Recommended future research
Fragmented modelling of pipe, equipment and vessel nozzles	Studies often focus on one component or discipline boundary.	Interface loads may pass locally while the system remains fragile.	Develop benchmark multi-equipment models with shared geometry, load cases and acceptance criteria.
Limited uncertainty treatment	Friction, settlement, restraint gaps and installation tolerances are	Nozzle-load margins may be overestimated under	Apply probabilistic or robust optimisation to supports,

	often deterministic.	real construction variability.	routing and thermal displacement control.
Weak static-dynamic coupling	Thermal flexibility and vibration/pulsation checks are frequently sequential.	A low static nozzle load may coexist with high fatigue or pulsation risk.	Create combined workflows linking flexibility, acoustics, modal response and fatigue.
Insufficient transfer from global piping models to local nozzle assessment	Load components are manually interpreted or simplified.	Stress concentration, reinforcement and crack risks can be missed.	Automate load-case transfer into local shell finite-element and fracture assessment models.
Poor life-cycle verification	Design assumptions are rarely updated after installation and maintenance.	Field modifications can change nozzle reactions without formal review.	Use instrumented commissioning, digital twins and management-of-change records to maintain nozzle-load envelopes.



Figure 2. Future research roadmap linking benchmark modelling, uncertainty-aware optimisation, dynamic coupling, digital verification and auditable governance.

Editable diagram description: Recreate as five rounded roadmap cards connected by slim arrows, converging into a broad outcome band labelled validated life-cycle management of nozzle-load envelopes. Use muted blue and green fills, balanced white space, subtle shadows and a minimal interface-style footer band.

VII. PRACTICAL, POLICY, OR THEORETICAL IMPLICATIONS

For practitioners, the review supports a disciplined workflow in which nozzle loads are treated as governing design outputs, not late-stage check values. Early routing decisions should reserve space for flexibility, anchor points, maintenance access and dynamic restraints. Equipment vendors should provide load limits, thermal growth data and alignment requirements early enough to influence layout. Piping engineers should document not only whether loads pass, but why the selected support strategy is robust under credible operating and installation variations.

For institutions and asset owners, the implication is that nozzle-load governance should extend into procurement, construction and operation. Specifications should require traceable load cases, model revision control, field support verification and post-commissioning comparison between predicted and observed behaviour. Policy within operating companies should discourage undocumented field modifications to supports, springs and restraints,

because such changes can transfer loads back to critical nozzles.

Policymakers and regulators rarely prescribe nozzle-load methods in detail, yet they can influence practice by requiring traceable integrity management for hazardous facilities. Clearer expectations for model retention, management of change and verification of critical supports would improve accountability without replacing engineering standards.

Theoretically, the review positions flexibility as an interface property rather than a pipe-only property. It links beam-based stress analysis, local shell mechanics, machinery alignment, vibration and digital monitoring into a common load-path perspective. This framing helps explain why apparently compliant designs can fail operationally: the wrong part of the system may have been made flexible, or the right boundary condition may have changed after installation. The proposed perspective therefore strengthens both research design and engineering judgement.

VIII. CONCLUSION

Advanced flexibility analysis and nozzle-load optimisation are central to the integrity of critical piping connected to compressors, pumps and pressure vessels. Recent literature confirms that these systems cannot be judged through pipe stress ratios alone. The decisive issue is the controlled distribution of thermal, sustained, pressure, dynamic and occasional loads through the pipe-support-equipment system. Vessel-nozzle studies have refined understanding of local stress, reinforcement and collapse behaviour. Rotating-equipment studies and standards emphasise alignment, casing protection and vibration. Support and routing optimisation research shows that design variables can be formalised, while digital monitoring creates the possibility of comparing analytical assumptions with service behaviour.

The review contributes an integrated synthesis across these domains and identifies the need for life-cycle nozzle-load governance. The evidence points toward models that are coupled, uncertainty-aware, dynamically informed and linked to operational data.

Future progress will depend less on adding isolated calculation detail and more on creating auditable workflows that connect design, installation, commissioning and monitoring. In critical industrial systems, flexibility is not merely the capacity to move; it is the capacity to move without transferring unacceptable risk to the equipment that anchors the process. Ultimately, effective governance converts analytical compliance into durable operational confidence by making assumptions visible, testable and revisable throughout the asset life under credible operational change. This improves resilience, accountability and operational continuity where equipment interfaces govern system risk.

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