

A Hybrid Stage-Gate/Agile Model for Brownfield Debottlenecking Projects in Continuous Process Plants

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Abstract

This review investigates how structured project governance can be combined with adaptive execution to improve the delivery of brownfield debottlenecking initiatives in continuous process plants. The study addresses the persistent challenge of modifying operating facilities characterized by legacy equipment, incomplete technical information, tightly coupled process systems, constrained shutdown windows, safety-critical interfaces, and evolving engineering requirements. A structured literature review and conceptual synthesis were employed to examine brownfield retrofit practice, Stage-Gate governance, Agile engineering, lifecycle integration, risk management, digitalization, and implementation barriers across industrial settings. The analysis shows that conventional sequential delivery models provide valuable control and assurance but can respond poorly to emergent field conditions, while purely Agile approaches may lack sufficient rigor for capital authorization, process safety, configuration management, and regulatory compliance. The principal finding is that a deliberately integrated hybrid architecture can reconcile these competing requirements by using formal decision gates to protect technical integrity, investment discipline, and operational readiness, while iterative work cycles support rapid learning, multidisciplinary coordination, field verification, and progressive constraint resolution. The review further identifies lifecycle integration, risk-adjusted gate criteria, Management of Change, commissioning readiness, benefits verification, and clear escalation thresholds as essential features of effective implementation. Digital twins, predictive analytics, condition-based monitoring, and improved data governance emerge as important enablers for future practice. The study concludes that hybrid delivery is most effective when tailored to project complexity, operational risk, and organizational capability rather than applied uniformly. It recommends empirical validation across multiple process industries, stronger integration of digital decision-support tools, and further research on optimal combinations of gate rigor, iteration length, decision authority, and adaptive engineering practices.

Keywords: Brownfield debottlenecking; Stage-Gate governance; Agile engineering; continuous process plants; risk-based decision-making; project lifecycle integration

Introduction

Brownfield Debottlenecking in Process Plants

Brownfield debottlenecking in continuous process plants involves removing capacity, reliability, energy, hydraulic, thermal, control, or operability constraints from an existing facility while preserving as much of the installed asset base as technically justified. Unlike greenfield development, the engineering problem is bounded by legacy equipment, process topology, occupied plot space, existing utilities, operating procedures, regulatory commitments, and production obligations. These conditions make debottlenecking an exercise in selective intervention. Early retrofit

research therefore framed debottlenecking as a constrained flowsheet-modification problem in which existing units may be modified, replaced, or supplemented to accommodate higher throughput without reconstructing the process architecture (Harsh, Saderne & Biegler, 1989).

The brownfield setting also introduces a distinctive project-risk profile because modifications must coexist with an operating asset. In manufacturing environments, incremental growth through plant expansion or renewal can offer competitive advantage, but interaction between project execution and concurrent operations creates risks that are materially different from those encountered on

greenfield sites (Warchol & Amadi-Echendu, 2007). Consequently, debottlenecking begins with disciplined diagnosis of the true limiting constraint. The apparent bottleneck may be a vessel, exchanger, compressor, pump, column, reactor, control valve, utility header, storage interface, or operating policy; increasing capacity at one point can simply transfer the limitation downstream. Bottleneck Tree Analysis demonstrates the value of tracing hierarchical constraints and evaluating debottlenecking options against operational, environmental, and economic criteria rather than treating maximum throughput as the sole objective (Teng et al., 2020).

From a process-engineering perspective, brownfield improvement is inseparable from retrofit and revamp practice. Retrofit projects demand detailed knowledge of existing process conditions, equipment margins, piping configurations, utility balances, instrumentation, and site constraints before feasible alternatives can be generated (Rangaiah, 2016). Project engineering must therefore integrate process design with constructability, procurement, shutdown planning, tie-in management, commissioning, and production-loss considerations; the number of possible revamp alternatives can make front-end evaluation more demanding than comparable new-build work (Reddy, 2016). This is particularly important in continuous plants, where modifications to interconnected units can alter pressure profiles, heat duties, separation performance, recycle behaviour, control interactions, and safety margins.

Debottlenecking is not limited to increasing nameplate capacity. It may also seek greater energy efficiency, lower emissions, improved product quality, reduced utility consumption, enhanced reliability, or recovery of latent capacity. Process intensification offers one pathway by improving transport and reaction rates, combining functions, reducing equipment footprint, or replacing conventional operations with more compact alternatives where technically justified (Rao, 2016). Likewise, retrofit process-integration methods can screen numerous streams and identify energy-saving opportunities without requiring complete redesign; an industrial dairy application showed that systematic decomposition could substantially reduce problem size while retaining

attractive retrofit solutions (Bergamini et al., 2021a). In an operating milk-powder facility, structured bridge analysis similarly demonstrated how process constraints, engineering judgement, economics, and heat-integration opportunities can be combined to formulate practicable retrofit alternatives (Bergamini et al., 2021b).

Evidence from refinery applications further illustrates the economic significance of targeted brownfield intervention. Graphical Pinch Analysis applied to an existing Kuwaiti crude-distillation heat-exchanger network identified retrofit modifications capable of reducing utility demand and producing substantial operating-cost savings with a short payback period (Alhajri et al., 2021). Such findings reinforce a central principle of brownfield debottlenecking: value arises from identifying the minimum effective change that releases a material operational constraint while avoiding unnecessary capital exposure.

Comparable optimization logic is relevant in developing industrial contexts. Nigerian research on integrating solar technologies into small-scale manufacturing highlights the practical importance of adapting new technical solutions to existing production infrastructure and resource conditions (Sunday & Omoegun, 2018). Related work on hybrid solar installations emphasizes load-distribution optimization and the need to match added capacity with existing system demand rather than treating expansion as an isolated equipment decision (Sunday & Omoegun, 2019). Asset-condition evidence is equally important: field assessment of existing infrastructure in Nigeria demonstrates the necessity of establishing actual physical condition before intervention decisions are made, a principle directly applicable to aging brownfield plant equipment, structures, and interfaces (Bolaji et al., 2019).

Complexity of Continuous Plant Modifications

Continuous plant modifications are intrinsically complex because they alter systems that must remain technically stable, safe and economically productive while engineering knowledge is still evolving. In brownfield debottlenecking, a change to one unit can propagate through upstream and downstream equipment, utilities, instrumentation, control loops and protection layers. This systems interdependence

means that a seemingly local intervention may change flow regimes, pressure balances, energy demand or contingency requirements elsewhere. Network-integration modelling similarly shows that introducing a new energy carrier into established infrastructure creates interactions across generation, storage, conversion and distribution functions, illustrating why brownfield modifications must be assessed at system rather than component level (Adeniji et al., 2019).

Complexity is intensified by the dynamic behaviour of continuously operating equipment. Thermal systems, for example, respond to variations in load, operating conditions and control strategy through coupled changes in energy consumption and performance, making accurate prediction essential when equipment or operating envelopes are modified (Sunday et al., 2019). Electrical modifications present comparable challenges because grounding, protection and network configuration must be optimized as an integrated architecture rather than as isolated hardware changes, particularly where existing infrastructure restricts design freedom (Shittu et al., 2020).

Physical asset condition further complicates brownfield execution. In a South African precious-metal processing plant, condition-based maintenance required identification of critical assets, interpretation of vibration data and anticipation of abnormal equipment behaviour before failure, demonstrating how legacy condition and incomplete performance information can influence intervention timing and plant availability (Ngoma, Mativenga & Pretorius, 2020). Brownfield teams must therefore reconcile as-built documentation with actual field conditions, equipment degradation, undocumented modifications, access limitations and restricted shutdown windows before finalizing work packages.

The challenge is not exclusively technical. Process-industry changes can simultaneously alter organizational responsibilities, operating procedures, interfaces and risk controls. Integrated safety-change management therefore requires technical and organizational consequences to be evaluated together, particularly where modifications can influence major-accident hazards (Gerbec, 2017).

For continuous process plants, these interacting uncertainties make purely linear execution difficult because scope maturity develops progressively through inspection, engineering analysis, operations feedback and risk review. A hybrid Stage-Gate/Agile architecture is consequently pertinent: formal gates can preserve technical assurance, configuration control and authorization discipline, while iterative work cycles accommodate field discoveries, evolving constraints and multidisciplinary learning.

Limitations of Conventional Delivery Models

Conventional project delivery models are founded on sequential planning, predetermined scope, approval hierarchies, and the assumption that uncertainty can be reduced before execution begins. These characteristics provide governance discipline, but they are less effective when brownfield debottlenecking projects evolve through field discoveries, operational constraints, and changing technical information. Traditional governance frameworks can strengthen accountability and compliance, yet excessive procedural rigidity may slow decisions and constrain adaptation when conditions depart from the original plan (Fadero et al., 2018).

Evidence from engineering and construction environments shows that project-management capability alone does not guarantee consistent success. Variations in organizational maturity, management processes, and contextual demands influence performance, indicating that standardized delivery systems must be adapted to individual projects (Pretorius, Steyn & Jordaan, 2012). This limitation is particularly important in continuous process plants, where shutdown windows, tie-in conditions, production priorities, equipment degradation, and latent design constraints can alter previously approved solutions.

Agile project-management research challenges the assumption that extensive front-end planning is sufficient for projects characterized by uncertainty. Cross-industry evidence indicates that organizations outside software development increasingly require practices permitting iterative planning, rapid feedback, and responsive adjustment as knowledge develops (Conforto et al., 2014). Empirical comparison of traditional and Agile approaches

further demonstrates that the models differ materially in planning intensity, control mechanisms, team organization, and responsiveness to change, making exclusive reliance on either potentially restrictive in complex environments (Eder et al., 2015).

Large-scale international evidence suggests that Agile practices can improve project efficiency and stakeholder satisfaction, while hybrid Agile–traditional arrangements are used where projects require both control and adaptability (Serrador & Pinto, 2015). However, pure Agile delivery is not suitable for brownfield process modifications because safety assurance, investment authorization, engineering verification, configuration control, and regulatory compliance require decision points. The Stage-Gate/Agile literature therefore provides a more appropriate direction: structured gates can preserve governance and investment discipline, while iterative sprints, frequent reviews, and cross-functional collaboration increase responsiveness and information flow between formal decisions (Cooper & Sommer, 2016). For brownfield debottlenecking, the principal limitation of conventional delivery is not structure itself, but insufficient flexibility within that structure to accommodate emergent technical knowledge without losing control.

Review Aim and Analytical Scope

This review examines how a hybrid Stage-Gate/Agile model can improve the planning, governance, and execution of brownfield debottlenecking projects in continuous process plants. Its principal aim is to establish a structured analytical basis for combining the assurance and decision discipline of Stage-Gate governance with the adaptability, iterative learning, and cross-functional responsiveness associated with Agile delivery. The review is therefore positioned at the intersection of capital-project governance, process engineering, brownfield modification, operational risk, and adaptive project management.

The analytical scope encompasses the full debottlenecking lifecycle, from constraint identification and opportunity framing through feasibility assessment, engineering development, procurement, shutdown preparation, installation, commissioning, and post-implementation performance verification. Particular attention is

given to the conditions that distinguish brownfield environments from conventional greenfield projects, including legacy equipment, incomplete plant information, restricted access, live-process interfaces, production continuity requirements, safety-critical modifications, and limited shutdown windows.

The review also evaluates how governance intensity should vary according to technical uncertainty, operational risk, scope maturity, and implementation complexity. Rather than treating Stage-Gate and Agile as competing methodologies, the analysis considers how they may be integrated into a complementary delivery architecture. This provides the foundation for assessing where formal decision gates are essential, where iterative execution is advantageous, and how both approaches can be coordinated to improve responsiveness without weakening technical integrity, cost control, safety assurance, or operational reliability.

Hybrid Governance for Brownfield Projects

Stage-Gate Control in Capital Projects

Stage-Gate control provides a disciplined governance architecture through which capital projects progress from an initially uncertain opportunity toward increasingly mature investment and execution decisions. Rather than treating project development as an uninterrupted sequence of engineering activities, the approach divides work into defined stages separated by decision gates at which technical maturity, commercial justification, risk exposure, resource requirements, and strategic alignment are assessed. Each gate therefore functions as a management control point at which decision-makers may authorize continuation, request further development, redirect the project, defer commitment, or terminate an unattractive opportunity before additional capital becomes irreversibly committed (Cooper, 2008).

This logic is particularly important for brownfield debottlenecking in continuous process plants, where premature commitment can expose operating assets to production disruption, safety risk, scope growth, and costly rework. Front-end project decisions are frequently made when information remains

incomplete, yet choices made during this period strongly influence subsequent project configuration and value. Effective governance consequently requires systematic clarification of objectives, alternatives, uncertainty, assumptions, and decision criteria before progressing toward detailed design or implementation (Williams & Samset, 2010). Within a debottlenecking context, gates can therefore be aligned with opportunity confirmation, concept selection, feasibility, engineering-definition maturity, final investment authorization, construction readiness, commissioning readiness, and benefit verification.

Governance effectiveness, however, depends on more than the existence of formal gate reviews. Project-management methodology and governance context interact in shaping project performance, indicating that structured processes must be supported by appropriate decision rights, accountability, sponsorship, and organizational oversight (Joslin & Müller, 2015). Governance arrangements must similarly balance stability with sufficient flexibility to address project-specific conditions; organizational enablers such as authority structures, communication mechanisms, institutional routines, and competent personnel are essential for translating governance principles into effective project decisions (Müller, Pemsel & Shao, 2015). In brownfield facilities, this means gatekeepers should include appropriate representation from operations, process engineering, maintenance, safety, reliability, project controls, procurement, and business leadership rather than allowing investment progression to depend solely on project-management assessments.

Human capability is equally important because gate quality depends upon the competence of those producing and interrogating the evidence presented for authorization. Capability-development frameworks emphasize alignment between workforce competencies, organizational objectives, knowledge transfer, and operational performance across distributed functions (Falemi, Akhigbe & Akin-Oluyomi, 2020). Professional attributes, communication, diligence, and effective coordination similarly contribute to organizational effectiveness, reinforcing the need for competent gate participants

capable of challenging assumptions and maintaining decision discipline (Onche, Adenekan & Sabboh, 2021).

Leadership quality also shapes whether governance controls operate substantively or merely become procedural formalities. Evidence from Southern African institutional settings highlights the importance of ethical leadership, accountability, and implementation discipline in converting policy intentions into realized outcomes (Enaifoghe, Dlamini & Agwuna, 2021). For capital projects, this implies that gate decisions should be evidence-driven, transparent, traceable, and resistant to schedule pressure or sunk-cost bias.

Nevertheless, Stage-Gate control need not imply inflexible execution. Manufacturing experience demonstrates that formal gates can coexist with iterative activities within stages, preserving executive control while allowing teams to respond rapidly to emerging information (Cooper & Sommer, 2018). This distinction is fundamental to brownfield debottlenecking: gates should establish minimum assurance requirements and authorization boundaries, while the engineering work between gates may remain iterative. Such an arrangement provides the governance backbone required for the proposed hybrid model, protecting capital, process safety, technical integrity, and operational continuity without preventing adaptive problem-solving as plant knowledge develops.

Agile Practices in Engineering Delivery

Agile practices provide engineering teams with mechanisms for managing uncertainty through incremental planning, short feedback cycles, transparent priorities, and continuous multidisciplinary interaction. In brownfield debottlenecking, these practices are particularly relevant because engineering assumptions frequently evolve after field verification, operations review, constructability assessment, or discovery of undocumented plant conditions. Manufacturing research demonstrates that selectively tailoring Agile practices to complex technical planning can improve responsiveness to emerging problems while retaining the stability required by industrial environments (Brandl et al., 2021).

Rather than attempting to freeze all requirements before detailed engineering, Agile delivery decomposes work into manageable increments that permit progressive validation. Physical-product development experience indicates that Scrum-inspired routines, visual planning, frequent reviews, and iterative decision-making can reduce bureaucracy and accelerate responses to changing technical requirements, although adaptation is necessary because physical engineering cannot replicate software Agile literally (Borba, Trabasso & Pessôa, 2019). Early engineering design similarly benefits from iterative modelling and validation, particularly when requirements and boundary conditions remain uncertain and digital engineering tools can rapidly test emerging alternatives (Enkler & Sporleder, 2019).

Within brownfield projects, Agile practice should therefore centre on prioritized engineering backlogs, short work cycles, daily coordination, interdisciplinary reviews, rapid escalation of constraints, and frequent engagement with operations and maintenance personnel. Evidence from South Africa further indicates that methodology compatibility with organizational needs and working conditions influences perceived Agile performance, particularly regarding project time and cost (Chiyangwa & Mnkandla, 2018).

Adaptability under constraint is equally relevant to operational decision-making. Nigerian evidence from disruption conditions demonstrates how established activity patterns can shift rapidly when external restrictions alter available options, reinforcing the value of responsive planning when original assumptions no longer hold (Ajayi, Alaka & Tiamiyu, 2020). Likewise, routing decisions within congested and poorly connected Lagos networks illustrate the importance of continuously adjusting execution choices as constraints and system conditions vary (Tiamiyu & Alaka, 2020).

Integrating Governance With Adaptive Execution

Integrating governance with adaptive execution requires a project architecture that distinguishes between what must remain controlled and what should remain responsive. In brownfield debottlenecking, investment authority, process

safety, technical assurance, configuration integrity and readiness for plant intervention require formal governance, whereas engineering development must accommodate emerging field information, operational feedback and changing constraints. Project governance consequently establishes decision rights, accountability and escalation mechanisms without necessarily prescribing every execution activity undertaken between authorization points (Turner, 2020).

Hybrid delivery operationalizes this distinction by combining predictive controls with iterative working practices. Empirical evidence indicates that hybrid approaches can preserve performance against conventional measures of budget, schedule, scope and quality while achieving stronger stakeholder outcomes, demonstrating that adaptability need not be obtained by abandoning managerial discipline (Gemino, Reich & Serrador, 2021). For brownfield projects, formal gates can therefore establish acceptance criteria while Agile cycles determine how multidisciplinary teams progressively satisfy them.

Effective integration also requires deliberate tailoring rather than mechanical combination. Hybrid project environments demonstrate that organizations select and combine practices according to technological uncertainty, organizational characteristics, and the nature of work, making contextual fit fundamental to implementation effectiveness (Azenha, Reis & Fleury, 2021). This is particularly relevant when field verification reveals undocumented piping, degraded equipment, inaccessible tie-ins, or unexpected process interactions requiring rapid redesign without bypassing approved safety boundaries.

Adaptive governance further depends upon mechanisms that permit rapid decisions while retaining transparency and institutional accountability. Experience under highly uncertain conditions demonstrates that agility and robustness can coexist where governance systems support information exchange, decentralized response and continuous learning while maintaining overarching coordination (Janssen & van der Voort, 2020). South Africa's pandemic response likewise illustrates the operational importance of coordinated institutional

adaptation when established systems confront rapidly evolving circumstances (Ikwegbue et al., 2021).

Digital architectures can strengthen this balance by enabling traceability, distributed coordination and transparent transactions across interconnected systems. Blockchain-based peer-to-peer energy models illustrate how decentralized operational decisions can function within defined rules, verification structures and governance mechanisms (Shittu et al., 2021). Applied to brownfield debottlenecking, the hybrid principle is therefore controlled adaptability: Stage-Gate governance defines mandatory assurance boundaries, while iterative execution accelerates learning, constraint resolution and engineering responsiveness within those boundaries.

Brownfield Debottlenecking Lifecycle Integration

Brownfield debottlenecking should be managed as an integrated lifecycle rather than as a sequence of isolated engineering tasks. The lifecycle begins with constraint identification, where operating data, field observations, maintenance history, process simulations, and stakeholder knowledge are combined to distinguish the governing bottleneck from secondary symptoms. Data-driven spatial analysis illustrates the broader value of locating concentrated problem zones before intervention, because poorly targeted improvement can relocate rather than eliminate system constraints (Alaka, Tiamiyu & Bolaji, 2021). In a process plant, this diagnostic discipline is essential before capacity targets, equipment modifications, or tie-in concepts are authorized.

Front-end definition then converts the identified constraint into a technically and economically credible project opportunity. Experience from large industrial projects shows that weak front-end loading is strongly associated with later scope change, schedule disruption, and cost escalation, whereas disciplined definition improves the quality of investment decisions before major expenditure is committed (Jergeas, 2008). For brownfield debottlenecking, this stage should establish the existing operating envelope, validate design bases,

identify interfaces with live systems, determine allowable shutdown exposure, and screen alternative solutions against safety, operability, constructability, maintainability, and expected throughput gain.

Detailed engineering must subsequently preserve lifecycle integration by connecting process design with mechanical, piping, electrical, instrumentation, civil, control, and operations requirements. Existing assets cannot be assumed to perform according to original drawings or nominal ratings; actual condition and service history must inform modification decisions. Repeated-load testing research demonstrates the importance of validating material and asset behaviour under realistic service demands rather than relying solely on nominal design assumptions (Alaka & Tiamiyu, 2019). The implication for brownfield plants is that engineering maturity should progress alongside field verification, equipment inspection, constructability review, and configuration reconciliation.

As design matures, management of change becomes a central lifecycle control. Process-industry evidence shows that technical and organizational changes can interact in ways that materially affect safety, requiring readiness assessments that consider procedures, responsibilities, competencies, and operational controls together (Levovnik & Gerbec, 2018). Procurement and fabrication should therefore be synchronized with approved design maturity, while long-lead items, temporary systems, prefabricated modules, and tie-in packages are prioritized according to shutdown criticality rather than procurement convenience.

The execution phase is particularly sensitive because continuous plants concentrate substantial work into short outages or turnarounds. South African evidence from power-plant outage projects identifies effective planning and risk management as major determinants of cost and schedule performance, with weak risk practices contributing to overruns (Hlophe & Visser, 2018). Shutdown timing should also reflect equipment condition and consequence of failure rather than fixed intervals alone; risk-based approaches can improve availability while controlling financial and safety exposure (Hameed & Khan, 2014).

Commissioning must be integrated before construction completion rather than treated as an end-stage activity. A structured commissioning strategy can reduce plant downtime by determining whether new systems should be commissioned directly, in advance, or in parallel with existing operations (Lawry & Pons, 2013). Industrial-delivery research further shows that commissioning represents the point at which earlier technical and organizational integration is tested in practice, making cross-functional relationships important throughout the project lifecycle (Kirsilä, Hellström & Wikström, 2007).

Lifecycle integration should continue after start-up through stabilization, performance testing, constraint revalidation, and benefit measurement. Debottlenecking success is not demonstrated merely by mechanical completion; it requires evidence that the modification has produced the intended production, reliability, energy, or economic improvement without introducing unacceptable new constraints. Benefits-realisation research emphasizes that project value depends on translating delivered outputs into measurable operational outcomes and sustained organizational value (Serra & Kunc, 2015). At every lifecycle transition, predefined acceptance criteria should therefore connect technical deliverables, operational readiness, residual risk, and expected benefits so that unresolved issues are visible before authorization advances and lessons generated during execution are deliberately carried forward into subsequent decisions. Within a hybrid Stage-Gate/Agile model, lifecycle integration consequently links formal maturity gates with iterative engineering, field learning, risk review, commissioning feedback, and post-start-up verification, ensuring that decisions remain connected from initial constraint diagnosis to demonstrated plant performance.

Risk-Based Hybrid Decision Framework

A risk-based hybrid decision framework for brownfield debottlenecking should regulate project progression according to uncertainty, consequence severity, technical maturity, and reversibility of decisions rather than imposing identical governance

requirements across all activities. Continuous process plants contain tightly interconnected equipment, utilities, control systems, safeguards, and operating procedures; therefore, apparently localized modifications can generate consequences far beyond the immediate intervention. Conventional risk registers are often insufficient because brownfield uncertainty extends beyond identifiable hazards to include incomplete drawings, uncertain equipment condition, evolving scope, hidden interfaces, operational assumptions, and stakeholder dependencies. A broader uncertainty-management perspective is therefore required throughout project development and execution (Ward & Chapman, 2003).

Within the proposed model, Stage-Gate controls establish formal decision boundaries, while Agile cycles generate and refine the evidence required to pass those boundaries. Each gate should assess process safety, design maturity, constructability, operational readiness, cost confidence, schedule exposure, interface risk, and residual uncertainty. Risk evaluation should also consider the strength of available knowledge because numerical probability alone can create false confidence when evidence is weak, or assumptions remain poorly validated (Aven, 2016). Accordingly, projects with high-consequence uncertainty should require more stringent gate criteria than low-risk, reversible modifications.

Complex projects also exhibit feedback effects that make risks interdependent rather than isolated. Technical changes may affect schedules, procurement choices may influence shutdown readiness, and production pressure may alter decision behaviour. Such interactions can make conventional event-by-event risk treatment inadequate where systemic relationships dominate project outcomes (Williams, 2017). Brownfield teams should therefore map dependencies among process equipment, utilities, control systems, construction interfaces, temporary facilities, tie-ins, commissioning activities, and operating procedures before approving execution.

Network-based analysis reinforces the importance of identifying vulnerable points and capability gaps. Research on accessibility across poorly connected Nigerian road networks demonstrates how system

Table 1: Illustrative Risk-Based Hybrid Decision Framework for Brownfield Debottlenecking

<i>Decision Stage</i>	<i>Typical Brownfield Risk</i>	<i>Stage-Gate Control</i>	<i>Agile Execution Practice</i>	<i>Escalation Trigger</i>	<i>Expected Decision</i>
Opportunity identification	Misdiagnosed bottleneck	Validate production constraint and business need	Short diagnostic cycles and operations feedback	Conflicting operating evidence	Proceed, reassess, or reject
Concept selection	Incomplete alternatives	Compare safety, value, operability and feasibility	Iterative option screening	High technical uncertainty	Select concept or extend study
Feasibility development	Hidden interfaces and legacy conditions	Confirm design basis and risk profile	Field verification and rapid design updates	Undocumented plant conditions	Advance or return for refinement
Detailed engineering	Design change and interface conflict	Verify design maturity and configuration control	Multidisciplinary sprint reviews	Safety-critical design deviation	Approve, hold, or escalate
Shutdown readiness	Schedule congestion and tie-in failure	Confirm work packs, permits and readiness	Daily coordination and constraint removal	Critical-path slippage	Execute or defer
Commissioning	Start-up instability	Verify testing and operating readiness	Rapid issue resolution loops	Unsafe or unstable operation	Continue, pause, or revert
Post-start-up review	Benefits not realised	Confirm throughput and reliability gains	Iterative performance tuning	New bottleneck emerges	Optimize or initiate new cycle

configuration can produce uneven exposure to service limitations, illustrating the value of analysing constraints as interconnected rather than isolated phenomena (Alaka, Ajayi & Bolaji, 2020). Similarly, identification of emergency-response coverage gaps demonstrates how inadequate system capacity can become visible when spatial and operational dependencies are examined systematically (Tiamiyu, Alaka & Ajayi, 2021). In brownfield plants, analogous analysis can reveal single-point failures, insufficient utility redundancy, congested tie-in zones, limited maintenance access, or inadequate contingency capacity.

The framework should also distinguish risk by decision criticality. Low-consequence and reversible engineering choices may be delegated to Agile teams, whereas changes affecting containment, safeguarding systems, major rotating equipment, or irreversible capital commitments should require elevated governance. Formal Management of Change processes are particularly important in brownfield facilities because apparently minor modifications can cumulatively alter operating

envelopes, responsibilities, procedures, and hazard controls (Saleem & Kovach, 2014).

Risk decisions are also influenced by individual and organizational attitudes. Project research demonstrates that decision-makers' risk orientation can shape their interpretation of threats, opportunities, and expected performance, potentially introducing optimism bias or excessive conservatism into project choices (Qazi, Daghfous & Khan, 2021). South African engineering and construction evidence likewise indicates that structured risk-management capability contributes to project success, while weak implementation and limited practical knowledge reduce effectiveness (Chihuri & Pretorius, 2010).

Localized operational interventions can additionally affect system-wide performance. Evidence from Nigerian arterial transport networks shows that concentrated loading and unloading activities can disrupt broader traffic flow, demonstrating how actions at individual nodes propagate through interconnected systems (Bolaji & Ajayi, 2021). Brownfield debottlenecking exhibits the same principle: increasing compressor capacity may expose downstream restrictions, while modifying

heat recovery may shift constraints to furnaces, cooling systems, or separation equipment.

Implementation Challenges and Future Priorities

Implementing a hybrid Stage-Gate/Agile model for brownfield debottlenecking requires more than combining two project-management methodologies. Its effectiveness depends on whether established plant governance, engineering systems, contractual arrangements, workforce capabilities and digital infrastructure can support controlled adaptation. Brownfield organizations frequently operate with deeply embedded functional boundaries, legacy procedures and approval structures developed around sequential project delivery. Industry 4.0 implementation research similarly demonstrates that technological transformation is conditioned by interacting organizational, strategic, technological and human factors rather than technology acquisition alone (Hoyer, Gunawan & Reaiche, 2020).

A major challenge concerns cultural acceptance of iterative engineering. Operations personnel may regard Agile practices as insufficiently controlled, while project teams may perceive established gate reviews as bureaucratic impediments. The hybrid model therefore requires explicit differentiation between adaptable execution practices and non-negotiable assurance requirements. Comparative manufacturing evidence indicates that developing economies face particularly significant internal capability and organizational barriers when adopting advanced industrial technologies, reinforcing the importance of organizational readiness before methodological transformation (Raj et al., 2020). Contracting strategies may create additional friction where engineering contractors are rewarded for fixed deliverables rather than progressive problem resolution, making commercial alignment an important implementation priority.

Legacy information represents another substantial constraint. Brownfield facilities may contain outdated drawings, undocumented modifications, fragmented maintenance histories and incompatible data platforms. Manufacturing evidence suggests that advanced technologies are implemented

unevenly, with foundational data, connectivity and analytics capabilities determining whether more sophisticated applications can deliver value (Frank, Dalenogare & Ayala, 2019). Hybrid delivery therefore requires a reliable information baseline in which field verification, configuration management and document updates occur continuously rather than being deferred until project completion.

Digital twins provide a promising future mechanism for integrating design, operating data and iterative decision-making. Their deployment in process industries, however, is constrained by model complexity, data availability, interoperability, organizational capability and difficulties representing physical processes accurately enough for decision support (Perno, Hvam & Haug, 2021). These limitations suggest that future brownfield applications should develop digital twins progressively, beginning with critical systems and high-value bottlenecks rather than attempting immediate plant-wide replication.

Workforce capability is equally decisive. South African manufacturing research identifies deficiencies in skills, organizational structures, education and contextual readiness as significant impediments to sustainable Industry 4.0 adoption (Maisiri, van Dyk & Coetzee, 2021). Hybrid brownfield teams consequently require competencies spanning process engineering, project governance, Agile facilitation, operations, data analytics, safety management and systems thinking. Skills research further indicates that digital transformation changes the combinations of technical and human capabilities required in manufacturing, creating a need for continuous reskilling rather than episodic training (Maisiri & van Dyk, 2021).

Future priorities should also include predictive maintenance and condition-informed project selection. Advanced monitoring and data analytics can identify degradation patterns before functional failure, allowing debottlenecking opportunities to be coordinated with reliability interventions and planned shutdowns (Zonta et al., 2020). Automated pattern recognition offers a complementary direction. Nigerian research applying template-matching techniques demonstrates the broader capability

of computational systems to detect significant patterns within complex datasets, supporting future investigation of analogous approaches for anomaly and constraint identification in industrial environments (Ejofodomi et al., 2014).

Digital-twin development should ultimately progress toward bidirectional integration between physical assets and virtual representations, supported by industrial connectivity, artificial intelligence and continuously updated data streams. However, unresolved issues concerning interoperability, cybersecurity, modelling accuracy and scalable data architectures remain important research priorities (Fuller et al., 2020). Accordingly, future validation of the proposed hybrid framework should extend beyond conceptual development to longitudinal industrial case studies comparing schedule predictability, engineering rework, shutdown performance, safety outcomes, throughput improvement and benefits realization. Such research should determine not merely whether Stage-Gate and Agile can coexist, but which combinations of gate rigor, iteration length, decision authority and digital support are most effective under different levels of brownfield complexity and operational risk.

Conclusion

This review examined how structured project governance and adaptive execution can be integrated to improve the delivery of brownfield debottlenecking initiatives in continuous process plants. The study's objectives were achieved by establishing the distinctive characteristics of brownfield modification, evaluating the limitations of conventional delivery models, examining Stage-Gate control and Agile engineering practices, and integrating these perspectives into a lifecycle-oriented and risk-based hybrid framework.

The analysis showed that brownfield debottlenecking is inherently complex because technical modifications must be executed within operating facilities characterized by legacy assets, incomplete plant information, safety-critical interfaces, constrained shutdown windows, and tightly coupled process systems. These conditions make purely sequential delivery models insufficiently

responsive, while purely Agile approaches lack the governance rigor required for investment authorization, process safety, configuration control, and regulatory assurance. The principal finding is therefore that hybridization offers a more appropriate delivery architecture when it is deliberately designed rather than mechanically combining methodologies.

The review further demonstrated that formal gates should be aligned with technical maturity, residual risk, constructability, operational readiness, and benefits realization, while iterative work cycles should support rapid learning, field verification, multidisciplinary collaboration, and progressive constraint resolution. Lifecycle integration is essential because value is created not only through successful installation but through commissioning, stabilization, and verified improvement in throughput, reliability, energy performance, or operating resilience.

Accordingly, organizations should implement risk-adjusted gate criteria, clearly defined escalation thresholds, integrated Management of Change processes, continuous configuration control, and multidisciplinary governance teams. Agile practices should be tailored to engineering realities rather than transferred directly from software development. Future implementation should also prioritize digital twins, predictive analytics, condition-based monitoring, and stronger data governance to improve decision quality. Further empirical research is recommended to validate the proposed framework across multiple process industries and to determine the most effective combinations of gate rigor, iteration length, decision authority, and digital support under differing levels of operational complexity and uncertainty.

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