Machina™: A Unified Design-to-Execution Well Optimization Suite with Real-Time Closed-Loop Fracturing

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Abstract
Hydraulic fracturing optimization has historically been segmented across disconnected workflows including pre-stage design, field execution, post-stage diagnostics, and historical analysis. While real-time downhole diagnostics, surface automation, and analytical platforms have matured independently, integration into a unified real-time feedback control framework has remained limited in field deployment. ProFrac has solved that problem with Machina™.

Machina™ is an integrated well optimization suite that unifies:
• Treatment design
• Earth model enablement
• Real-time subsurface measurement
• Mid-stage intervention
• Frac hit detection and mitigation
• Live pad-level operational tracking
• Historical performance analytics
• Supply chain and cost optimization
• Real-time water quality analysis

These components operate within a single continuous data architecture in which engineering assumptions, measurement data, and execution parameters coexist within a shared state environment. This structural integration enables closed-loop behavior not only within a stage, but across the full lifecycle of completion programs.

Within Machina™, Closed-Loop Fracturing (CLF) operates as a supervised feedback control module in which real-time subsurface state variables are continuously evaluated against defined performance envelopes. When deviations are detected, corrective inputs are issued through rule-based control logic and executed at surface with millisecond-scale latency. Subsurface response is subsequently remeasured and validated within the same stage, closing the intra-stage control loop.

This completions suite is architected to ingest and normalize data streams from any third-party source including sensors, service providers, enterprise systems, and external analytics platforms. These inputs are integrated directly into the control loop to enhance decision fidelity, real-time operational responsiveness, and system-level optimization across both subsurface performance and surface execution. This open architecture ensures that Machina™ functions as a control platform rather than a closed ecosystem, allowing operators to incorporate evolving diagnostic technologies without redesigning the execution framework.

In field use cases involving real-time intervention, cumulative perforation efficiency degradation was 18% during non-intervention stages and 12% during mid-stage intervention stages, representing a 6-percentage-point absolute reduction (33% relative). This preservation of completion efficiency reflects not only improved operational control but measurable economic value creation. Increased stimulation efficiency supports more consistent well performance, improved reservoir contact effectiveness, and enhanced asset-level capital efficiency.

Machina™ establishes a continuous engineering and operational feedback loop extending from treatment design through real-time execution and into historical performance learning, enabling sustained optimization at both the stage and program level.

Nomenclature

PE = Perforation Efficiency

ΔPE = Change in Perforation Efficiency

d(PE)/dt = Perforation Efficiency Degradation Rate

CLF = Closed-Loop Fracturing

HHP = Hydraulic Horsepower

1. Introduction

Well performance optimization typically occurs in discrete phases:

1. Pre-stage modeling
2. Field execution
3. Post-stage evaluation
4. Cross-well performance review

These phases often operate on separate systems with limited data continuity. As a result:

- Design assumptions are not dynamically validated mid-stage
- Execution adjustments are manual and inconsistent
- Diagnostic interpretation is frequently delayed
- Learning cycles are slow

Closed-loop fracturing has been referenced in industry literature for years. In most cases, the term has described either surface rate-holding automation or post-stage diagnostic-informed design updates. While these implementations represent meaningful advances, they remain functionally open-loop because subsurface feedback does not directly modify execution during the active stage.

Machina™ was developed to address this structural limitation.

Within Machina™, subsurface measurement, trigger logic, and surface actuation are integrated into a real-time feedback loop. Intervention occurs mid-stage while the fracture system remains responsive. Execution changes are reflected at surface within milliseconds through coordinated pump control.

Machina™ ingests and contextualizes real-time operational and environmental data streams including water quality variability, frac-hit indicators, and surface system constraints. It can autonomously adjust treatment parameters during execution. These adjustments may include rate and proppant schedule modification, mitigation responses to fracture interference, and real-time cost optimization through reduced non-productive chemical expenditure and more efficient material utilization. In this framework, logistics, chemistry, subsurface response, and equipment execution are no longer treated as isolated variables but as interconnected components within a unified optimization system.

This implementation satisfies the engineering definition of closed-loop control: system output directly influences system input during operation.

2. System Architecture Overview

Machina™ is structured as an integrated engineering suite composed of four main functional domains:

1. Design and Treatment Modeling
2. Measurement and Subsurface State Estimation
3. Closed-Loop Fracturing Module
4. Live Pad-Level Operational Tracking

All domains operate on a shared data architecture, ensuring continuity between modeling assumptions, execution behavior, and historical performance analysis.

3. Design and Pre-Stage Modeling Layer

Machina™ incorporates treatment design capabilities including:

• Stage-level parameterization
• Rate schedule modeling
• Cluster distribution modeling
• Historical benchmarking
• Pad-level comparative performance analysis

Design intent is stored within the same environment used for execution monitoring. This ensures that mid-stage evaluation references original engineering assumptions rather than isolated surface metrics.

The continuity between design and execution enables validation of modeled expectations against measured subsurface response.

4. Dynamic State Assessment and Optimization

The measurement layer is source-agnostic and architected to ingest, normalize, and contextualize data streams from any internal or third-party system. This includes subsurface diagnostics, surface instrumentation, chemical performance metrics, offset well surveillance, logistics systems, and enterprise platforms. Both structured and unstructured data, including real-time sensor feeds, service provider datasets, laboratory analysis, and operational or supply chain inputs, are integrated into a unified state model that continuously evaluates system performance and identifies optimization opportunities during execution.

Surface pressure alone is a composite signal incorporating pipe friction, perforation friction, fracture propagation response, and equipment variability. Real-time downhole feedback enables isolation of perforation friction components and estimation of cluster-level flow contribution during active pumping. Machina™ allows the controller to evaluate and look for improvement to provide measurable gains in operational efficiency, treatment effectiveness, and capital performance in real time. From a control-systems perspective, the measurement layer provides dynamic state estimation rather than passive monitoring.

4.1 Measurement Application 1: Seismos' Use of Seismos Acoustic Friction Analysis within Machina™ Environment

For a closed-loop system to function reliably, the measurement layer must provide continuous, quantitative state estimation that is sensitive to controlled pressure signals and stable under high-rate, high-proppant stimulation conditions. The ability to resolve dynamic system response in real time is essential to enable timely corrective intervention and validating corrective action within the same stage. Within the Machina™ environment, acoustic friction analysis is not deployed as a standalone technology but as an integrated state variable feeding directly into the closed-loop decision engine.

Seismos utilizes acoustic friction analysis to directly measure perforation friction and calculate perforation efficiency in real time. The system quantifies live hydraulic performance during active stimulation, measuring how flow distribution evolves throughout the stage. Unlike imaging-based downhole tools that provide geometric diagnostics after the fact, acoustic friction analysis delivers actionable state information during pumping.

The system operates under active pumping conditions and acquires high-resolution pressure-wave data in high-noise frac environments. As pressure energy propagates through the wellbore, it interacts differently with confined tubular flow than with fluid discharging through perforations. These distinct physical mechanisms produce different signatures in the pressure-wave response. Because pipe friction and perforation friction influence wave behavior through fundamentally different processes, their effects are inherently separable within the measured signal.

This separation does not rely on assumed friction factors or steady-state interpretations that mathematically lump pipe, perforation, and near-wellbore friction into a single response. In conventional step-down analysis, these components cannot be independently resolved, and flow contribution must be indirectly inferred from modeled pressure relationships. In contrast, the separation exists in the physics of the wave itself. With pipe friction and perforation friction independently measured, the system calculates perforation efficiency and uniformity index directly from observed friction behavior.

The temporal resolution captures transient response during rate interventions, enabling detection of measurable shifts in perforation efficiency and degradation trends. Signal stability is maintained through sand loading transitions and variable pumping conditions, enabling quantitative validation that prescribed interventions have altered hydraulic distribution and improved stimulation efficiency.

This measured cause-and-effect response enables true closed-loop execution.

5. Closed-Loop Fracturing Module

Closed-Loop Fracturing (CLF) operates within Machina™ as a supervised intra-stage control subsystem that maps real-time subsurface state variables to coordinated surface actuation via predefined control logic, operating within established equipment and operational constraint boundaries.

5.1 Definition of Closed-Loop in This Context

Closed-loop control is defined here as a system in which subsurface state is measured during active stimulation, deviation from the expected performance envelope is detected algorithmically, corrective action is prescribed, surface actuation is executed immediately, and subsurface response is subsequently measured and validated. This continuous feedback cycle ensures that intervention decisions are based on real-time system behavior and that corrective actions produce measurable and verifiable performance outcomes.

Many prior industry implementations have incorporated elements of feedback, including automated rate control or diagnostic-informed design adjustments. However, Machina™ represents the first field-deployed system in which subsurface measurement, prescriptive decision logic, and surface actuation are fully integrated into a live intra-stage control loop. Rate adjustments commanded by the decision layer are executed in real time, with latency limited to system communication and coordinated pump response, typically measured in milliseconds.

This distinction is critical to true closed-loop operation. Intervention occurs during the active stage while the fracture system remains dynamically responsive, allowing corrective action to alter the stimulation trajectory and preserve completion efficiency rather than simply observing or reacting after degradation has already occurred.

5.2 Trigger Logic

Inputs to the decision layer include:

- Real-time PE
- d(PE)/dt degradation
- Fluid distribution behavior
- Hydraulic diameter stability
- Surface equipment metrics

Trigger criteria may include:

- PE below defined threshold
- Accelerated PE degradation beyond envelope
- Friction imbalance exceeding tolerance

When trigger criteria are met, Machina prescribes:

- Rate interventions magnitude
- Duration
- Recovery profile

Subjective interpretation is removed from the intervention pathway.

5.3 ProPilot Execution Layer

ProPilot functions as the deterministic execution layer within the Machina™ closed-loop control architecture, translating real-time diagnostic insight and prescriptive control recommendations into immediate and repeatable physical system response. When real time data detects deviation from expected performance, Machina™ evaluates the deviation and prescribes a corrective intervention. ProPilot executes these commands in real time, enabling coordinated adjustment of pumping parameters while the fracture system remains dynamically responsive.

Execution responsiveness is fundamental to closed-loop operation. ProPilot is designed to react to Machina™ control commands with minimal latency, ensuring that rate interventions, ramp modifications, or load redistribution actions are applied immediately following validated subsurface triggers. Because the measurement layer provides continuous real-time state estimation, ProPilot is able to execute precisely timed interventions that allow the system to observe and validate subsurface response under controlled conditions. This tight coupling between measurement, decision, and execution ensures that corrective actions are not only prescribed but physically realized.

Execution variability in conventional frac operations often introduces oscillatory behavior, transient pressure instability, and uneven pump loading. These effects can distort subsurface signal interpretation and reduce confidence in diagnostic measurements. ProPilot minimizes these sources of execution noise by coordinating pump response, managing load distribution across the fleet, and maintaining stable hydraulic conditions during and after intervention. This allows the measurement layer to observe clean system response, ensuring that intervention outcomes can be quantitatively validated.

By enabling rapid, coordinated, and repeatable execution in direct response to real-time measurement triggers, ProPilot completes the closed-loop control cycle within Machina™, ensuring that subsurface insight is translated into immediate and measurable operational action.

6. Field Validation Results

Perforation efficiency degradation was measured from evaluation checkpoint through mid-stage and end-of-stage.

Three categories were analyzed:

1. Low Performing – Intervention
2. Low Performing – No Intervention
3. High Performing – No Intervention

Mid-Stage ΔPE:
Intervention: 5%
Untreated: 9%

Final ΔPE:
Intervention: 12%
Untreated: 18%

Intervention reduced cumulative degradation by approximately 33%.

Notably, untreated high-performing and low-performing stages converged to similar cumulative degradation. Closed-loop mid-stage intervention altered the degradation trajectory rather than temporarily correcting early-stage inefficiency.

7. Live Pad-Level Operational Tracking

Machina™ provides real-time pad-level visibility including:

• Stage progression
• Pump health metrics
• Rate and pressure tracking

• Fleet efficiency metrics
• Simul-frac coordination

Multiple active pads can be monitored within a unified environment. Execution stability metrics are continuously evaluated to preserve measurement integrity and control validity.

8. Historical Data Integration and Cross-Pad Learning
All stage and pad data are archived within Machina™, enabling:
• Cross-pad PE degradation comparison
• Intervention response benchmarking
• Basin-level trend analysis
• Performance envelope refinement

This establishes a longitudinal learning loop feeding back into future design assumptions. Closed-loop learning extends beyond individual stages into program-level optimization.

Conclusion

Machina™ represents a unified well optimization suite that integrates pre-stage design, real-time subsurface measurement, intra-stage intervention, live pad-level operational tracking, historical performance analytics, supply chain cost optimization, and real-time water quality analysis within a single continuous engineering environment. By consolidating these traditionally disconnected workflows, Machina™ enables operators to transition from retrospective analysis to real-time performance control and program-level optimization.

Closed-Loop Fracturing operates within Machina™ as a true feedback control system in which subsurface state directly informs surface execution during active stimulation. Real-time data ingestion, algorithmic deviation detection, and live surface actuation allow corrective intervention while the fracture system remains dynamically responsive. Subsurface response is then measured and validated quantitatively, ensuring that intervention outcomes are both observable and repeatable.

Field validation confirms that intra-stage intervention preserves perforation efficiency and alters the degradation trajectory relative to untreated stages. This preservation of stimulation efficiency supports improved fracture distribution consistency, enhanced reservoir contact effectiveness, and stronger overall completion performance. The integration of multi-source real-time data streams further enables operators to incorporate operational, logistical, and subsurface variables into a unified decision framework.

By establishing a continuous feedback loop that extends from treatment design through live execution and into historical performance learning, Machina™ enables sustained optimization at both the stage and asset level. This integrated architecture allows operators to improve completion effectiveness, increase operational consistency, and enhance capital efficiency across entire development programs.