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Rig Brain: Pieces Exist
A Transition from Advisory to Autonomous Drilling

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Abstract

In drilling, every little bit counts. Rig rates and chemicals, service companies tickets and even as far as opportunity costs, all add to a huge cost: thus any small incremental improvement can have serious impact, and serious weight, when leveraged across wells.

The industry has always been built on hard targets; run safe, efficient and sustainable operations while meeting a KPIs that ever seem to tighten constantly. Over time, many solutions have emerged to predict the unpredictable and augment crews on the rig floor, from remote operation centers and automated tools, to edge computing. All of these tools have value, and well proven effect in the industry, yet far too often they exist in silos.

The missing link is not new technology, but something to tie it all together. This thesis names this missing link the “Rig Brain”: a unified, operator-owned layer connecting operational memory, decision logic, safety checks, and vendor applications as one system. The concept is simple: take what we already have, connect it, and let it work as one brain, helping people on the rig while paving the way for bounded autonomy.

The pieces to build this are in place today, meaning that the technology already exists, yet the indusry needs operators to stand up in their contracts, demand interoperability, clear data rights and strong cybersecurity. Once operators lead, the industry can shift from a patchwork of tools to a true system-wide approach, delivering safer, more efficient, and more sustainable drilling operations ready for the future.

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List of Abbreviations

1. **AFM** – Automated Fluids Monitoring
2. **AI** – Artificial Intelligence
3. **API** – Application Programming Interface
4. **BHA** – Bottom Hole Assembly
5. **DP** – Dynamic Positioning
6. **DSATS** – Drilling Systems Automation Technical Section
7. **ESG** – Environmental, Social, and Governance
8. **GUI** – Graphical User Interface
9. **HMI** – Human–Machine Interface
10. **HSI** – Human Systems Integration
11. **HSE** – Health, Safety, and Environment
12. **ILT** – Invisible Lost Time
13. **IADC** – International Association of Drilling Contractors
14. **IDS** – Intrusion Detection System
15. **IP** – Intellectual Property
16. **KPI** – Key Performance Indicator
17. **LOA** – Levels of Automation
18. **MPD** – Managed Pressure Drilling
19. **MQTT** – Message Queuing Telemetry Transport
20. **NPT** – Non-Productive Time
21. **NOVOS** – National Oilwell Varco Operating System (automation platform)
22. **OPC UA** – Open Platform Communications Unified Architecture
23. **OT** – Operational Technology
24. **P-TAF** – Psychological Technology Adoption Framework
25. **POB** – Personnel on Board
26. **ROC** – Remote Operations Center
27. **RTOC** – Real-Time Operations Center
28. **ROP** – Rate of Penetration
29. **RPM** – Revolutions Per Minute
30. **ROS** – Rig Operating System
31. **SLB** – Schlumberger
32. **TCO** – Total Cost of Ownership
33. **WITSML** – Wellsite Information Transfer Standard Markup Language

Chapter 1. Introduction

As with any industry, the drilling industry keeps on facing challenges with maintaining lower costs for delivering products—oil and gas wells—while also maintaining the safety and efficiency expected from the industry regulators and standards. The traditional manual-based control operations and crew experiences are often overstretched and not viable anymore. The complexity of operations, as a result of enhancing technologies, demands a higher level of attention and expertise to deliver the consistent, safe, and efficient expectations. Even the most skilled, who are capable of monitoring and maintaining the operations, currently would and are benefiting from technologies to help them overcome the fast pace of operations and reduce human error. (Macpherson, Cayeux, Thorogood, & King, 2013)

Automation offers a way forward. Solutions and technologies such as Remote Operations Centers (ROCs)—allowing specialists and vendors to monitor multiple rigs (Thorsen, Sæverhagen, & Dagestad, 2013), or digital twins—simulating equipment conditions in real time – for predictive maintenance (Bimastianto et al., 2020), and also edge computing—bringing processing power closer to the rig Alanazi, Altuwaijri, Bagabas, Khan, & Otaibi, 2025). Where approaches such as closed-loop trajectory systems—in directional drilling—have already proven success and landed wells within centimeters of target zones without incidents (Baker Hughes, 2020). All these examples prove that technology works. Yet all of these remain isolated in a sense, without full connection between others, so we remain as of today—isolated, vendor-specific, and uncoordinated—meaning the benefits are uneven and often short-lived.

1.1 Background

When examining operations on a drilling rig, we find that drilling has relied mainly on manual decisions—where the driller manually adjusts parameters such as weight on bit, or rotary speed, or the mud engineer altering the mud properties based on field judgments. In a well written program, these decisions are usually made based on a trend from surrounding wells and the experience the crews have. This manual approach has worked, yet it is no longer adequate based on technological advancements obtained and industry expectations. For that, drilling crews are dynamic and utilize the technologies to sustain the expected level of awareness. (Macpherson et al., 2013)

Economics reinforces the need for change. Economics comes strongly into context when looking at the unproductive times in the drilling schedules, which can account for 15% on average—and higher with invisible lost time. Daily rig rates hover around $100,000 and sum up to ten times this number—especially when combining all daily costs (Accenture, 2022).The incentive is high to improve—even if by a little—and that is only considering improvements, not also the cost of preventing an incident, which some cannot be reversed or translated into cost. Environmental and ESG pressures add to the case: operators are required to prove measurable reductions in emissions, waste, and overall footprint (World Oil, 2021) .In short, the combined drivers of safety, economics, workforce changes, ESG expectations, and advancing technology have created unprecedented demand for automation.

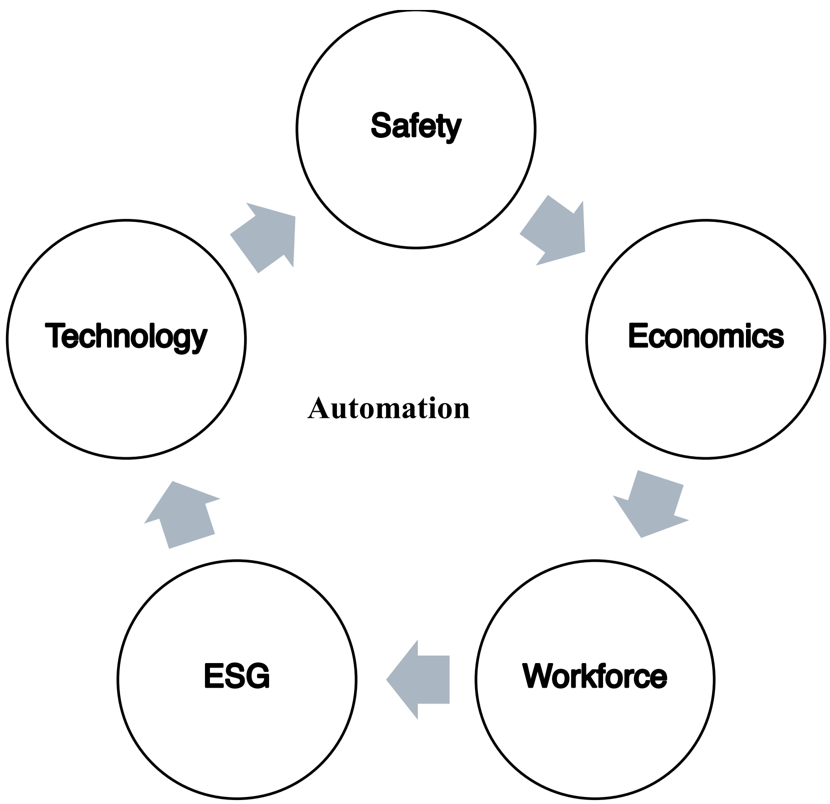

Figure 1: Automation Drivers

1.2 Problem Statement

Despite the technological advancements and automation leaps, the drilling industry as a whole has not yet shifted to full automation. The single successes of these developments are visible, yet not at a fleet-wide step. Most automations are still on the advisory level, which stops short of execution, leaving the crews to perform and take on the responsibility. Where others, such as predictive models, drift out of calibration, at which point crews start distrusting the system. Finally, the interface of human-machine often overwhelms the crews rather than aids them. (Roberts, Flin, Millar, & Corradi, 2021)

Often also, the success stories from case studies highlight the success yet omit the difficulties or failures behind them, leaving managers unsure whether the result can be scaled up fleet-wide or it was a single isolated success. For example, liner running gains in the North Sea may not apply to rigs without the same equipment or infrastructure. (Baker Hughes, 2021) Autonomous directional drilling has been proven technically, but only under tightly controlled, sensor-rich conditions. (Arndt, Hoffart, & Gabrielsen, 2025)

The outcome is isolated advancements, rather than an industry-wide coordinated shift. What is missing in this equation to full automation is present, and it's not capabilities, it's integration. The integration of all these advancements into a layer that brings all these technologies together and serves as the setting-stone towards full autonomy.

1.3 Research Objectives

This thesis addresses the industry question of how drilling can move from fragmented advisory tools to an integrated and bounded autonomy system—while still delivering safe, efficient, and environmentally friendly operations with no compromises.

To answer this, these five objectives are set as follows:

Clarify frameworks and taxonomy—Provide clear definitions of advisory, automated, and autonomous systems to avoid confusion and misaligned expectations. (de Wardt et al., 2024)

Identify integration gaps—Examine technical and contractual barriers that prevent vendor systems from working together.

Analyze drivers and value creation—Explore how safety, economics, ESG, and organizational factors shape automation adoption. (Accenture, 2022; World Oil, 2021)

Draw lessons from other industries – Look at maritime and manufacturing precedents for successful orchestration / coordination layer. (Millward et al., 2025; Integration Objects, 2025; ISA, 2024.

Propose Rig Brain as a framework—Present an operator-owned layer model that includes data rights, cybersecurity, governance, and contract levers for adoption.

1.4 Methodology

The research takes a synthesis approach, combining four elements:

Literature review: peer-reviewed papers, industry journals, and standards from SPE, IADC, and DSATS to establish the state of drilling automation. (Macpherson et al., 2013; Thorsen et al., 2013)

Standards analysis: evaluation of WITSML, OPC UA, and IEC 62443 to understand their maturity and role in enabling interoperability. (Energistics, 2025); (OPC Foundation, 2025); (ISA, 2024).

Case studies: review of projects such as Equinor's autonomous drilling, ADNOC's digital transformation, Aramco's edge AI, the Hess–Nabors collaboration, and Baker Hughes deployments. (Millward et al., 2025); (Bimastianto et al., 2020); (Alanazi et al., 2025,); (Gillan, Isbell, & Visitew, 2018); (Baker Hughes, 2020; 2021).

Cross-industry comparison: analysis of maritime control systems and Industry 4.0 manufacturing as precedents for vendor-neutral orchestration "coordination layer".

(Millward et al., 2025); (Integration Objects, 2023); (ISA, 2024); Montes, Ashok, & van Oort, 2025).

The goal is to bridge academic analysis with practical application, offering insight that operators, contractors, and service companies can act on.

1.5 Thesis Structure

The thesis is structured as follows:

Chapter 1 – Introduction: sets context, outlines the problem, objectives, and methods.

Chapter 2 – Theoretical Framework and Taxonomy: covers levels of automation, process states, human-system integration, and standards.

Chapter 3 – Drivers and Value Creation: explains the pressures shaping adoption, including safety, economics, ESG, and workforce.

Chapter 4 – Case Studies in Drilling Automation: reviews field deployments and lessons learned.

Chapter 5 – The Missing Link: Vendor-Neutral Orchestration: introduces the Rig Brain concept and its components.

Chapter 6 – Data, Governance, and Cybersecurity: examines ownership, interoperability, and governance issues.

Chapter 7 – Recommendations and future look: provides strategic guidance for operators, vendors, and regulators, and sets out the path forward.

Chapter 8 – Thesis conclusions.

Chapter 2. Theoretical Framework and Taxonomy

For drilling automation to progress, technical teams, managers, and stakeholders need a clear and consistent language. Without it, vague terms like “smart,” “intelligent,” or “autonomous” create confusion, misaligned expectations, and poor investment decisions. The aim of this chapter is to lay down the theoretical foundations and taxonomy that define drilling automation. These frameworks help explain where the industry stands today and highlight what is missing.

Drilling automation draws from control systems theory, human factors engineering, and industrial automation, but must adapt to the unique challenges of drilling: harsh and variable conditions, uncertain subsurface environments, and the high cost of failure. Any classification must consider not only the machine but the interplay between humans, automation systems, and the unpredictable operational setting. (Accenture, 2022)

2.1 Levels of Automation Framework

The Levels of Automation (LOA) framework, borrowed from aviation and automotive, is a useful way to describe the spectrum of human–machine roles in drilling.

Table 1: Levels of Automation (LOA) Across Industries

Level	Aviation Example	Automotive Example	Drilling Example
Manual	Pilot manually flies aircraft	Driver fully controls vehicle	Driller adjusts WOB and RPM manually
Advisory	Flight management settings	Lane departure warning	Digital twin recommends ROP/WOB.
Automated	Autopilot under supervision	Adaptive cruise control	MPD maintains annular pressure.
Autonomous	UAV flies without input	Level 5 self-driving car	i-Trak trajectory system closes loop.

Macpherson's Purdue model (2013) first applied it to drilling, and categorized it as follows: (Macpherson, Cayeux, Thorogood, & King, 2013)

1. Manual: The driller controls weight on bit and RPM directly.
2. Advisory: Digital twins suggest parameters, but humans decide.
3. Automated: Systems like Managed Pressure Drilling (MPD) maintain annular pressure with limited oversight.
4. Autonomous: Systems like i-Trak trajectory can close the loop with minimal human input.

	A	B	C	D	
	INFORMATION AQUISTION	INFORMATION ANALYSIS	DECISION AND ACTION SELECTION	ACTION IMPLIMENTATION	
DONE BY HUMANS	Manual	Memory Analysis	Human Decision	Manual Action and Control	0
	Non-Technical Artefact Supported	Non-Technical Artefact Supported	Non-Technical Artefact Supported	Non-Technical Artefact Supported	1
SUPPORTED BY AUTOMATION	Low Level Automation	Low Level Automation	Automated Decision Support	Step-by-Step Action Support	2
	Medium Level Automation	Medium Level Automation	Rigid Automated Decision Support	Low Level Support Action Execution	3
	High Level Automation	High Level Automation	Low Level Automation	High Level Support Action Execution	4
	Full Automation	Full Automation	High Level Automation	Low-Level Action Sequence	5
Done by Automation AUTONOMOUS	Full Automatic Information Acquisition including derived and inferred measurements, along with attributes such as uncertainty	Full Automatic Information Analysis including objective functions and error analysis relative to a mission plan	Full Automatic Decision Making, including the generation of options and decision selection	Low-Level Autonomous	6
				Medium-Level Autonomous	7
				Full Autonomous	8

Figure 2: LOAT from de Wardt el. 2016, adapted from Save et al. 2012 – (de Wardt, Cayeux, Mihai, Macpherson, Annaiyappa, & Pirovolou, 2024)

In practice, drilling operations often run at different levels at the same time. One subsystem might be automated while another is still manual. De Wardt and Cayeux expanded the model to reflect this "multi-agent" reality, where coordination between subsystems becomes the real challenge (Cao et al., 2024).

LEVEL	INFORMATION ACQUISTION	INFORMATION ANALYSIS	DECISION AND ACTION SELECTION	ACTION IMPLEMENTATION
0	Manual	Memory Analysis	Human Decision	Manual Action and Control
1	Artifact-Supported	Artifact-Supported	Artifact-Supported	Artifact-Supported
2	Low-Level Automation	Low-Level Automation	Automated Decision Support	Step-by-step Action Support
3	Medium-Level Automation	Medium-Level Automation	Rigid Automation Decision Support	Low-Level Support Action Execution
4	High –Level Automation	High –Level Automation	Low-Level Automatic Decision	High-Level Support Action Execution
5	Full Automation	Full Automation	High-Level Automatic Decision	Low-Level Action Sequence
6			Full Automatic Decision Making	Medium-Level Action Sequence
7				High Level Action Sequence
8				Full Automation

Figure 2: LOAT from de Wardt et al. 2016, after Save et al. 2012. The maximum level attainable for acquisition and information analysis caps out at level five. In drilling systems automation, this may not be applicable – Cayeux, Macpherson, Laing, Wylie, & Florence, 2024)

Conflicts are prevalent in automations where a hydraulics optimizer can recommend one-sided settings that may conflict with a pressure management system. Arbitration must exist or there will be no decision or an unsafe compromise. This is the reasoning behind why most field examples today are advisory and automated – not fully automated, hence advisory; operators have to set realistic expectations and plan their adoption stages accordingly.

For Rig Brain this architecture is relevant, since it demonstrates the industry is not failing due to a lack of automation pieces, but rather a lack of a higher-level system that can coordinate multiple levels simultaneously.

2.2 Process State Framework

Another enabler of automation is a standardized way of describing what the rig is doing at any given moment. Cayeux and Macpherson proposed mathematical process states for drilling, setting boundary conditions to each operations to be identified. (Cayeux et al., 2024)

These states—drilling, tripping, circulating, making connections—are defined by boundary conditions (pressure, torque, mechanical limits), with uncertainty estimates and transition rules.

The benefit is that multiple vendor systems can align on a single definition of the rig state. ADNOC and SLB have already used this in their RTOCs, improving anomaly detection and reducing false alarms (Bimastianto et al., 2020). For Rig Brain, such standardization is essential. A central orchestration layer cannot work if vendors each define "drilling" or "circulating" differently. Common states are the language through which subsystems would communicate.

2.3 Human Systems Integration

Automation is not possible without the human element. Human Systems Integration (HSI) is a concept developed by De Wardt and Sheridan, adapted from the aviation sector, which states that safety and performance rely on human decision-making and machine accuracy in unison. Automation can enhance our cognitive process by collecting, computing, and compressing data; however, this automation should not result in cognitive overload for the worker.

For example, adaptive automation can automatically provide more or less support depending on the circumstances. The cabin studies by Equinor showed that a cluttered design could cause alarm fatigue, confusion caused by information on screens, and physiological and ergonomic factors, leading to decreased situational awareness and performance. Therefore, managers must consider HSI an integrated part of the design process, not as an add-on. (Arndt, Hoffart, & Gabrielsen, 2025).

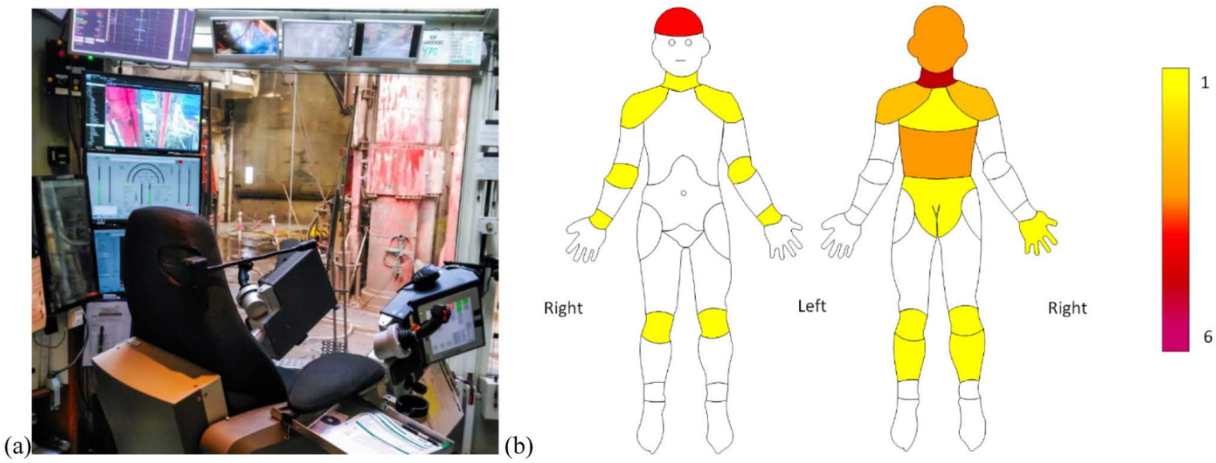

Figure 3: HMI - Human Machine Interface

The human–machine interface must be designed to maintain trust and oversight. A central brain cannot succeed unless the human operators understand, monitor, and intervene when needed.

2.4 Infrastructure and Standards

Scalability of drilling automation solutions can be attributed to two things. An underlying communications infrastructure and common standards for data formats and application/platform interoperability. Vendor systems don't interoperate very well without the two. Saudi Aramco has been operating WITSML based surveillance platforms for years. The first article describes how using standard data formats can enable vendors to plug in to the system and automate tasks with relative ease (Energistics, 2025). WITSML remains the primary standard for data interchange, but OPC UA, and MQTT have gained a foothold for secure, low-latency communication between surface and downhole systems (OPC Foundation, 2025). OPC UA is a good fit for safety-critical drilling applications because it is platform agnostic and has strong built in error handling. MQTT is a good fit for constrained edge computing environments because it is extremely lightweight. Edge computing also brought compute power to the rigsite, lessened dependency on satellite comms, and enabled real-time operation of AI and machine learning applications. Aramco's recent application of edge AI shows how local models can overcome bandwidth constraints and latency issues to allow for quicker decision making (Alanazi et al., 2025). This shift has also created new governance needs including secure ways to update models, manage access controls, incident response plans, and audit trails for compliance. Standards and supporting infrastructures help mitigate vendor lock-in, lower integration costs, and facilitate the scalability of automation. These are non-negotiables for the concept of Rig Brain: no central coordination layer, an orchestration, can be achieved without interoperable data pipelines and secure protocols.

Table 2: Standards and Infrastructure for Drilling Automation

Component	Example	Function
Data Transfer	WITSML	Standardized wellsite data exchange
Communication	OPC-UA / MQTT	Secure, low-latency system interaction
Edge Computing	Rigsite AI servers	Real-time inference without satellite dependence
Cybersecurity	IDS, encryption	Protect operational technology from attack

Technical feasibility and maturity of governance are two sides of the same coin and managers must recognize that no matter how sophisticated their technical capability may be, it is useless without the ability to secure and govern and manage risk. Automated deployment requires a significant investment in infrastructure, but once in place that infrastructure creates value and flexibility in the long term as the use of automation in drilling activities continues to evolve and scale.

2.5 Current Industry Position

In reality, the state of automation for drilling operations today is mixed. Some are near complete automation, such as tripping and fluid monitoring, with demonstrable benefits to efficiency. Others, such as real-time monitoring (ROCs, digital twins) are advisory only and require human decision-making in most cases. Closed-loop trajectory control has been demonstrated in the field, but only for a very limited range of conditions with extensive sensorization (Gillan, Isbell, & Visitew, 2018; Arndt, Hoffart, & Gabrielsen, 2025).

As Table 3 shows, the overall picture is a patchwork. Each domain—fluids, pressure control, trajectory, anomaly detection—sits at a different level of maturity. Where automation thrives is in discrete, repeatable workflows; where it struggles is in high-risk, multi-vendor orchestration. Aviation and automotive have already advanced toward domain-wide autonomy, but drilling is still piecing together function-specific gains.

This situation has both advantages and drawbacks. It allows operators to automate for the highest value-add, lowest risk tasks first, but it also means overall performance remains fragmented. To move further, orchestration/ coordination and governance will be essential—bringing together these subsystems into something more coherent, rather than treating autonomy as a linear journey to “full automation.

Table 3: Current Drilling Industry Position in Automation (based on references)

Function / Domain	Typical Current LOA	Source	Gap to Autonomy	Managerial Implication
Real-time monitoring (ROCs)	Advisory	BEACON centers, WITSML surveillance	Limited automation; still human interpretation	Build foundation, but not autonomy
Parameter optimization	Advisory-Automated	Digital twins give ROP/WOB advice	Execution remains human	Governance and trust needed for closed loop
Fluid monitoring	Automated	AFM detects barite sag in 30 min	Advisory on remediation	Fast ROI; candidate for scaling
Tripping & liner running	Automated	i-Trak improves speeds 13-100%	Requires human supervision	Automate repetitive tasks first
Directional drilling	Advisory-Autonomous (bounded)	North Sea closed-loop trajectory	Works only with dense sensing	Proof-of-concept autonomy

Managed Pressure Drilling	Automated	MPD maintains annular pressure	Autonomy limited by regulation & trust	Governance frameworks required
Multi-advisor orchestration	Advisory	Equinor-Halliburton orchestration	Arbitration still has manual fallback	Explicit governance gap
Human Systems Integration	Advisory support	Equinor cabin redesign	Automation undercuts trust if ignored	HSI training is essential
Risk detection / anomaly	Advisory-Automated	Hybrid unsupervised detection	Predictions not fully autonomous	Requires model governance
Cybersecurity & governance	Immature	Edge AI deployments	Autonomy expands attack surface	Integrate OT security with automation

Chapter 3. Economic Drivers and Value Creation

Cost alone is an incomplete economic basis for automating drilling. Automation is associated with multiple value streams: safety performance, environmental stewardship, process consistency, organizational competence, and more. Value must be measured, and to do that you must first assess the direct and indirect value streams and the amount of financial outlay required. Contextual factors must also be considered such as ROI in differing operational environments and organizational maturity. Vendor case studies present best-in-class and often short-term, narrow cost savings. But for automation to succeed, an in-depth economic assessment must be done to consider all costs and benefits, all risks and opportunities for value creation over the long term. The economic drivers for automation implementation are often dramatically different from one organization to the next, dependent upon the nature of work being performed and the organization's long-term objectives. The heterogeneity of automation's economic benefits requires an individualized, context-specific business case that goes beyond simple ROI and vendor estimates.

3.1 Direct Economic Benefits

The most direct and quantifiable advantage of drilling automation is the reduction of non-productive time (NPT) and invisible lost time (ILT) due to efficiency, standardization and proactiveness of operation to eliminate and prevent problems. A series of case studies show significant improvements in operation performance when implementing automation technologies on repetitive, high-frequency activities with human variability, enabling standardization and optimization (Macpherson et al., 2013).

Baker Hughes have domintrated how automation can be a useful tool with high safety outcome where in the Middle East operations have benifited. Using the trip speed advisory system, Baker Hughes saw 13% increase in trip speed on average for all hole sizes, translating into 8.4 hours of saved time per section, and more importantly, zero swab/surge incidents.(Baker Hughes, 2021)

This case shows a significant safety achievement demonstrating how automation can reach that goal of improved efficiency without compromises in risk management (Cayeux et al., 2024). Given a typical range of daily rig running cost of $30,000 to $150,000 depending on rig type, location, and market condition, the above time savings can be quite significant.

Automated fluids monitoring system implemented in Norway has an even more remarkable improvement for selective applications, where early detection and prevention can help avoid costly operational issues. By detecting barite sag in 30 minutes instead of manual checks every 6 hours, the system helped avoid string plugging and reduce NPT that would have contributed to stuck pipe incidents, costing the operation millions of dollars (Baker Hughes, 2023).

Offshore operations with rig costs frequently exceeding $100,000 per day and weeks of additional time to recovery from incidents, automation of condition monitoring can be justified by the avoided costs if just one significant issue can be prevented. Liner running in the North Sea also had significant improvement with advisory automation. Running speed increased from 414 meters per hour to 889 meters per hour, saving 13.8 hours of rig time, and again with zero swab/surge incidents (Baker Hughes, 2021). Overall, high-frequency, repetitive tasks with defined performance metrics have the most significant potential return on investment and should be the first to be considered for automation.

Table 4: Documented Efficiency Gains from Case Studies

Case Study	Automation Type	Measured Improvement	Value Impact
Middle East	Tripping automation	+13% tripping speed, 8.4 hrs saved	~$1M savings per rig/year
Norway	Fluids monitoring	Sag detection 6 hrs → 30 min	Prevented ~$2M loss
North Sea	Liner running	Speed 414 → 889 m/hr, 13.8 hrs saved	>$180,000 saved in one run
North Sea	Trajectory control	Landed within 2 m, zero NPT	Higher quality wells

Automation provides more than direct performance improvements. One of the biggest benefits is consistency. If operations run in a steady, predictable fashion, projects are easier to plan and companies are more confident pushing development forward.
For operators running several rigs or large campaigns, it helps with planning, cost control, and negotiating service contracts. Reliable performance also reduces the need for contingencies and can lower the risk profile of an entire project. Equinor in the North Sea, can be taken as a good example, where automated drilling allowed the project to move faster with fewer backup plans, resulting in lower overall cost and higher efficiency.

3.2 Safety and Risk Reduction Value

Avoided cost (AC) value represents a major portion of the Total Economic Value (TEV) for drilling automation and is a relatively uncontested form of economic value. AC is created by an automation system in the form of the following: (Cayeux et al., 2024; Baker Hughes, 2021)

- Intangible and indirect ways. This includes avoided incidents or penalties, lower insurance costs, evidence of responsible practices to regulators and insurers.

- Insurance premium discounts and performance-based regulations are already helping the industry unlock the value in AC because a no incident record demonstrates risk reduction efforts and help with demonstrating ALARP. There are many other ways to show value from these systems.

An important point to note is that the economic value created by automation in these forms is often a major portion of the total value stream of an automation project but goes unaccounted for in the return on investment calculations. This is because the cost is avoided, not accounted for, in the control group. (Goodkey, Fabo, Le Buhan, Cahalane, & Bisht, 2024)

Incident frequency has been consistently linked to automation, especially in offshore scenarios where the cost per incident is higher due to several factors that increase the total cost of an event. SLB's global study of offshore barriers concluded "unproven financial impact" was the primary barrier to automation in many offshore organizations today, but this report clearly ties deployment to fewer incidents as a key finding. In a survey of 30 D&C projects that had deployed automation systems, 22 of those reported a reduction in incidents that can be tied directly to automation deployment. They also point out that offshore operations have a higher cost per incident. In the same study they also note, "Reducing the frequency of incidents is one of the best arguments for the financial benefits of D&C automation." [F07 p.16] One of the many reasons for a higher cost per incident in an offshore setting is the amount of focus from media, regulators, and the public. (Goodkey, Fabo, Le Buhan, Cahalane, & Bisht, 2024)

The hybrid unsupervised anomaly detection system designed for drilling applications and field tested on multiple offshore installations had 100% recall on event detection with approximately 0.3 false alarms per event and a 15 second response time (Liu et al., 2025). A system that can catch all events at a level of fidelity that allows intervention before an event becomes a problem has the potential to save millions of dollars per avoided major loss event, whether it's a blowout, stuck pipe, or environmental incident. These events can cost companies tens to hundreds of millions of dollars and can take months or years to completely resolve with operations offline the entire time.

Equinor also automated a complex trajectory offshore drilling operation and finished with zero HSE incidents, while still outperforming the baseline in technical performance (Arndt, Hoffart, & Gabrielsen, 2025) This directly ties automation to safety value creation.

Regulatory compliance is another economic value stream that is often invisible. Audit trails/logs/evidence that risk is being reduced means operators have a lot more leverage with regulators and insurers. Robust model governance — with model cards, leakage checks, and consistent metrics — means it's much easier to demonstrate lower risk. This can lead to lower premiums, faster permits, fewer constraints, and better contract terms.

3.3 Environmental and ESG Value

ESG — environmental, social, and governance — has become the performance yardstick in oil and gas. It's no longer enough to demonstrate efficiency; the industry must prove to investors, regulators and communities that it operates safely, sustainably, and with good governance. Strong ESG performance is directly linked to economic validation and access to capital for operators.

Automation supports ESG performance in concrete ways. By optimizing drilling parameters, it helps to minimize emissions, real time monitoring and reduced risk of losses and environmental events, and remote supervision and operations reduce the number of offshore personnel, aircraft flights, and logistics, while also minimizing exposure. These improvements help reduce the footprint of a drilling campaign, now measured in permits, financing packages, and community reviews (World Oil, 2021).

The benefits are obvious, but credibility is important. Vendor claims on ESG performance in some cases are based on models, not actual operational data. For trust to be maintained companies will need to measure continually and verify with external validators. Those able to link automation to specific and measurable improvements in ESG performance will have a big leg up in permitting, capital attraction, and maintaining a social license to operate.

There is also a broader less measurable benefit: social license. In many jurisdictions, leadership on safety and environmental performance is required to maintain community and regulatory goodwill. Investments in visible and proven ESG connected automation can become like an insurance policy to guard against future restrictions, market access issues, or local stakeholder pushback.

3.4 Investment Requirements

Automation, however, is about more than the purchase of new tools. This capability brings with it often-hidden costs in establishing the appropriate infrastructure, securing the underlying systems, educating and training the workforce, and evolving the organization.

Aramco's deployment of leading-edge analytics use cases at the edge are a good example of how the infrastructure piece of the puzzle can be applied in real life: rugged edge devices that can withstand the rig environment, redundant levels of connectivity, and separate IT/OT networks for optimal system operations, all of which are wrapped in robust cybersecurity to mitigate and protect against external and internal threats. (Alanazi et al., 2025)

However, human capital costs are often the most significant, and most reliable till today. Successful organizations in this space invest in their workforce training across the board, from the driller to the roustabouts, to ensure that everyone fully appreciates both the power and the limitations of automation. It is only with the right talent development that trust is established and decisions made more effectively.

Beyond people and technology, the most significant shift may lie in the business change effort required. Elements such as trust building, proper incentive alignment, and cultivation of internal champions can be of high importance. Governance is another component that should be an investment, not an afterthought. Models should be continually validated and recalibrated as the surrounding conditions change. When done properly, this aspect can help safeguard performance, compliance, and long-term value.

Table 5: Categories of Investment in Drilling Automation

Category	Examples
Infrastructure	Edge servers, OPC-UA/MQTT, deterministic comms
Cybersecurity	IDS, encryption, access control
Human Capital	Training, digital academies, cross-skilling
Governance	Model validation, calibration, audit trails
Culture	Incentives, trust-building, champions

3.5 Return on Investment Analysis

Drilling automation return on investment (ROI) should be considered in two components, direct and indirect. First are the direct and more tangible benefits that will be quantifiable, starting from the day the system is deployed. These are the impact that most organizations will measure as the primary focus of the business case for automation. The second component is the more indirect and intangible benefits that are realized over time. This is the more challenging portion to quantify yet still provides value to the organization.

As mentioned before, too often the focus on the business case for automation remains only on immediate savings – minimizing hours lost, efficient crews, smaller headcount – where in reality, the bottom-line benefit often realized over time is more toward a reduction of incidents, ESG performance improvement, and capabilities gained with repeated use.

These advantages that are embedded in the organization through each deployment gain momentum and become more impactful to the business from project to project. Automation also adds portfolio value in terms of creating an ability to standardize across rigs with learning loops to build knowledge throughout the operator team, enhanced ability to negotiate with vendors as best practices become more transparent, simplified compliance requirements, and stronger access to capital and joint ventures from showcasing a technology leadership position in the industry.

However, the return of drilling automation will be directly correlated to the execution behind the deployment. With best practices and strong governance, automation can pay for itself almost immediately. With weaker compliance checks and balances and a workforce that is less trusting of the system due to cultural elements, then automation can also go the opposite direction. It’s not so much about the equipment but the readiness of the organization to embrace and operate in conjunction with automation.

Chapter 4. Case Studies in Drilling Automation

Drilling automation has evolved for 20 years from a combination of advisory systems, automated execution, bounded autonomy and pilot orchestration efforts. The broad range of implementations now delivers a view of both technical feasibility and current challenges. Case studies from across the industry do not just show performance improvements but also identify common roadblocks: data quality, communications reliability, governance maturity and organizational readiness.

This chapter surveys representative automation deployments which are categorized as follows: ROCs are the foundation; Automated remote directional drilling; Integrated offshore orchestration; Autonomous trajectory control; Edge computing and AI; MPD automation; Vendor automation platforms; Digital twins; Predictive maintenance; Vision-based safety and monitoring. A cross-case analysis follows with lessons for managers and operators. The stage is set in Chapter 5 for Rig Brain, the orchestration solution.

4.1 Remote Operations Centers: The Foundation

The first “significant” automation deployments were ROCs. Baker Hughes began the rollout of its BEACON centers in 2013 (Thorsen, Sæverhagen & Dagestad, 2013), an architecture that aggregated real-time data from multiple rigs and data of record, then centralized it for multidisciplinary review. BEACON proved a small team of SMEs could concurrently monitor and backhaul multiple rigs with prescriptive modeling, torque & drag simulations, and anomaly detection.

The concept also matured an organization-wide confidence in deferring to machine-guided decision making. At scale, Saudi Aramco launched its Real-Time Operations Center (RTOC), also built on the WITSML standards (Energistics, 2025). Aramco’s novelty was combining real-time drilling data with static datasets (BHA configs, DHRs, etc.) to provide additional context for anomaly detection. RTOCs have made a case that the right combination of structured data and expert interpretation can enhance early warning/anomaly detection and awareness of barite sag, stick–slip, torque inefficiencies, and other phenomena.

Two lessons from ROCs: the first being reduced dependence on rig-site people by shifting cognitive load to centralized teams of experts, and secondly that automation benefits are constrained when communications reliability or data integration is not present (ISA, 2024).

4.2 Automated Remote Directional Drilling

A major development in automation was achieved through the well-known collaboration between Hess Corporation and Nabors Industries, in the Bakken USA – back in 2017, which has frequently been cited as a benchmark for the transition from advisory tools to execution automation in directional drilling (Gillan, Isbell, & Visitew, 2018).

The case has not only been a technological and operational turning point and has also highlighted the organizational change aspects and catalytic effect on the uptake of higher automation levels that can be driven by operator–contractor partnerships.

The Hess–Nabors program has matured through different levels of automation and is first introduced in this level as a traditional advisory system, in which the directional driller was advised and guided through a real-time monitoring and decision-support system. Final decisions are still made and executed on the rigsite. The collaboration advanced along a path towards automated execution of directional operations, based on integrated navigation software with real-time trajectory calculation and optimization, which was combined with automated slide execution. The latter is a feature that removes the manual operation of the top drive during directional drilling.

Directional drillers in a remote operations center supervised these processes, retaining an option to intervene, if necessary, but monitoring multiple wells concurrently. The program has proven several outcomes:

First, through the integration of automation in the workflows, Hess and Nabors were able to standardize performance across wells and deliver consistent quality, which was less dependent on the individual skill level of staff on the rig.

This consistency became valuable as the industry has been impacted by the “crew change” effect, in which experienced employees have been retiring, and there were fewer people available to replace them in the same numbers. Second, the case is an example of how automation can change staffing configurations while still preserving safety and efficiency. Automated slide execution combined with remote supervision, required less directional drilling staff on the rig floor. Expertise was aggregated in operations centers, where experienced drillers could monitor and work multiple rigs at a time.

The case was not to do away with rig-based staff, but to re-define it. Rig crews would act as supervisors and safety monitors, while most directional decisions are made remotely, and automatically.

The Hess–Nabors experience, however, has also illustrated conditions for success. The system was dependent on resilient communications to ensure data integrity for real-time transmission and logging between the rig and the remote operations center. Loss of data or latency would force the system to fall back on manual mode. It has therefore become clear that not only is communications reliability a technical specification, but that it is also an essential element to build trust in automated workflows.

Equally important has been the governance protocols that have been defined to specify when and how human operators should override the automation. Automation can lead to ambiguity if roles and responsibilities are not clear. Hess and Nabors have developed rules for interventions to ensure rig crews, and remote operators, had clear expectations on when manual override was justified. In practice this has been very important to avoid hesitations or delays in response in safety-critical scenarios. Training has been another important component. Rig personnel and remote operators were provided with longer term exposure to the automated system to gain confidence and competence. This was costly and time-intensive, but crucial to prepare crews for early-warning recognition and to foster trust in the human–automation partnership. The case also illustrates that automation cannot be “plugged in” to existing processes but instead requires an investment in a dedicated program of cultural and technical adaptation. Finally, the collaboration demonstrated the criticality of aligning incentives between operator and contractor. Traditional contracting models, based on day rates or service fees, are anti-innovation and promote misaligned incentives. Hess and Nabors developed contractual frameworks that fairly shared risk and rewards between the parties. This contractual innovation has been critical to maintain motivation for the program, even during early challenges when fallback to manual processes was a practical alternative. The Hess–Nabors case study teaches that automation is not just a technology change program but also an organizational and contractual one. Automated remote directional drilling can work because it combined a number of technical elements (advanced navigation and execution software, but also robust communications, governance, training, and incentives). The case is evidence that automation can lead to better and more consistent results than manual workarounds, but only if it is supported by the right ecosystem of technology, governance, and culture.

4.3 Integrated Offshore Automation

A more recent project in 2025 with Equinor, Halliburton, Sekal and HMH [F06 p.3-7] validated that similar automation could also work across a multi-vendor value chain offshore drilling. In contrast to earlier single-vendor pilots, it demonstrated that surface and downhole systems from different suppliers could be orchestrated into a single workflow (Millward, Kabi, Marck, Laing, Welmer, Reber, Kjoesnes, & Kvammen, 2025)

The system was based on open standards such as OPC-UA and MQTT, so that equipment and software across the value chain could be linked. The key element was a set of "edge advisors" with domain-specific software agents for hydraulics, trajectory or surface efficiency. These received data, performed the analysis and generated recommendations, which were pushed to the rig for execution. Arbitration logic avoided conflicts between the recommendations of different advisors, while degradation paths ensured a safe fallback to manual or advisory mode when required. The integrated setup provided superior performance gains. The coordination of surface and downhole systems exposed and eliminated small inefficiencies that would otherwise accumulate to invisible lost time (ILT). Proactive detection of factors that cause disruptions also helped to anticipate them earlier, contributing to a reduction in non-productive time (NPT).

Automated validation also helped to ensure data quality and integrity, building confidence in the advisors' output – which is of particular importance in drilling automation. The study also revealed risks. For example, a lack of arbitration and governance would allow the output from different systems to compete in a way that could paralyze a decision or require an override manual intervention, thus defeating automation's trust. Another element that became clear, was that integration doesn't just impact processes, but people as well. Manual workarounds were removed, while crews had to be retrained on how to follow new workflows. Equinor therefore implemented structured change management alongside the technical work to ensure that crew members would develop the necessary confidence and trust in the system. In short, the Equinor–Halliburton–Sekal–HMH case had validated that automation across a multi-vendor value chain offshore was both technically and commercially feasible, but only if based on open standards, provided with arbitration and fallback mechanisms and supported by effective change management. Orchestration had thus emerged as the key enabler for scaling automation beyond isolated projects.

4.4 Aramco Edge Computing and AI

Saudi Aramco's deployment of generative AI and machine learning at the rig site was an example of a computing form that has come to be known as edge computing.

Edge computing systems move computing hardware and data closer to sensors at the physical location of a compute deployment rather than collecting all data and sending it to the cloud for analysis and decision-making. The rationale for edge computing systems at drilling rigs included low satellite bandwidth and issues with communications reliability in remote automation (Alanazi, Altuwaijri, Bagabas, Khan, & Otaibi, 2025).

Saudi Aramco's implementation of generative AI and machine learning on an edge deployment proved the technical feasibility and necessary governance to safely use advanced AI systems to improve operational drilling. Edge AI models were run on rugged edge servers at the rig site to avoid latency and reliability concerns with satellite communications to support real-time inference and decision-making.

The use cases for edge AI systems on drilling rigs included: a variety of sensor data, predictive models to estimate the risk of a stuck-pipe event, real-time adjustments to operational parameters to improve tripping efficiency, and GPS IoT time synchronization to provide accurate correlation of data across distributed systems.

The same case study also provides details on how AI was deployed at the edge. Edge AI deployments in drilling rigs included rugged edge servers for use in harsh and variable environments, local execution of AI models without the need for cloud connectivity, GPS time synchronization for distributed systems data correlation, and automated model update processes to safely update AI models without disrupting operations.

Yet, Edge AI systems for use in drilling and industrial automation face risk profiles and management challenges that are unique to both their capabilities and remote deployment locations. There is a need for strong governance frameworks for edge AI systems. Saudi Aramco has managed this risk by protecting its edge AI systems through model updates, access control measures, and incident response plans.

Governance requirements for edge deployment from this case study included model validation to ensure AI models will reliably perform before moving to production, access control measures to prevent unauthorized system or parameter changes, incident response procedures to recover from edge computing failures or cybersecurity incidents, and audit trails to log AI decision-making for compliance or incident review.

Proof-of-concept work early on showed data quality still matters regardless of AI sophistication. Day by day the need for governance and management grows with the autonomy of remote AI systems. Cybersecurity and monitoring are required to be built with more complexity for edge systems, and while Edge autonomy is beginning to mature in now, it requires ready infrastructure, cybersecurity preparedness, and strong governance frameworks as prerequisites for adoption, not just simple system upgrades.

The Saudi Aramco edge AI case study proved that it was possible to use advanced AI models for real-time inference and decisions at a drilling site without relying on communications that have variable latency. Autonomous drilling systems of the future will have to be able to have consistent communications reliability regardless of link quality or availability. From Governance, to cybersecurity, and data quality management and including investments may be required in addition to AI technology acquisition costs to be successful in this area.

4.5 Supplementary Case Studies – MPD, Vendor Platforms, Digital Twins, and Predictive Maintenance

Beyond the three enabling cases mentioned above, a number of other technologies have been introduced across the industry that enable automation, but in different ways. Each of these solutions has been successfully adopted in their respective domains, but taken as a whole, they present a picture of the siloed nature of current automation implementations and the need for orchestration. (World Oil, 2021)

First, one has to highlight the specific use case of Managed Pressure Drilling (MPD) automation. Noble and NOV separately launched the industry's first fully-integrated MPD control system (NOV, n.d – ref # 29)). By fully integrating automated pressure management with rig operating networks, the solution removed the need for specialist crews on site and improved information flow between drilling and pressure control teams. MPD automation is a representative example of bounded autonomy from above: a discrete safety-critical function that can be readily automated by itself. At the same time, MPD solutions bring out another issue—compatibility across functions: pressure management algorithms must be tightly coupled with other automation systems to prevent conflict.

A second major trend has been the development of vendor automation platforms. NOV's NOVOS [F9], Halliburton's LOGIX (Halliburton, n.d – ref # 17), and SLB's DrillOps (SLB, 2023) are three major examples of platforms that support a variety of process automation, trajectory optimization, and data aggregation services. Each of them is a mature, commercially-successful product deployed at hundreds of rigs across the industry, indicating that high-end automation has already become an industry standard.

Their limitation is also equally clear: each platform performs best in its home environment, and interoperability between vendor platforms is still low. This is one of the drivers of the need for a common framework for orchestration.

Digital twins have become a key technology in recent years. Kongsberg's SiteCom platform (Kongsberg Digital, n.d. ref #25) and the Digital Twin Consortium's open framework (Cao et al., 2024) are two examples that let operators model wells and rigs in a virtual environment, test possible outcomes, and run predictions. They can support remote operations and help spot anomalies, offering useful guidance to decision-making. Still, their value depends on the quality of the data going in, and their role today is mainly advisory — they guide decisions but don't carry them out.

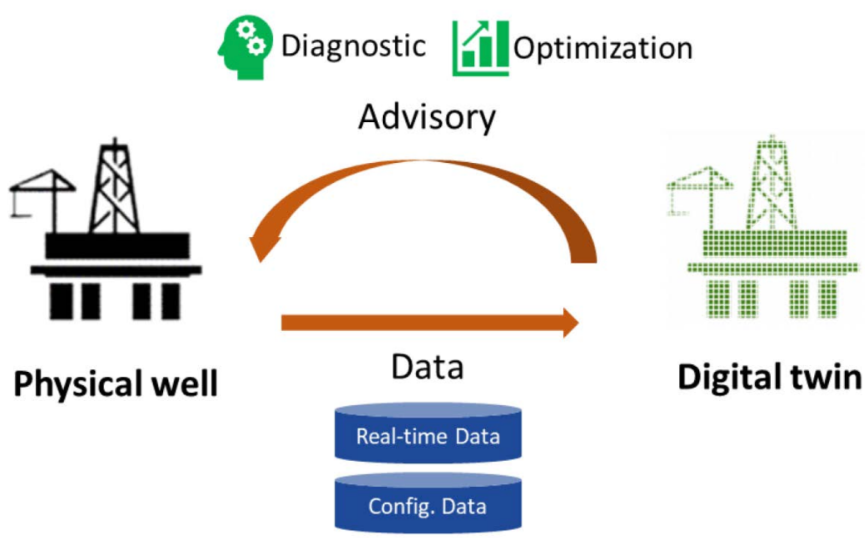

Figure 4: Digital twin applied for drilling advisory - (SPE 217960)

Predictive maintenance and anomaly detection has also become a growing area of AI applications in the drilling industry, where the power of automation and artificial intelagance was proved.

Recently this year, under the title of "A New Workflow of Drilling Anomaly Detection Based on Prior Knowledge and Unsupervised Learning" (Liu et al., 2025) has developed an unsupervised learning workflow that achieved high recall in anomaly detection on offshore drilling data - claiming 100% event-based recall in test cases, low false alarms. Montes et al. (2025) did a review of the current state of stuck-pipe prediction techniques and noted the improvements in early detection, while it was noticed the ongoing barriers to model generalization.

The value of these systems, are adding to the performance, as they minimize equipment downtime and aim to avoid accidents, but they do require clear governance to ensure that their predictions remain valid over time. Taken together, the secondary cases above show that drilling automation is a varied and siloed domain.

While each individual technology has utility in their respective area (pressure management, process automation, virtual modeling, or predictive analytics), none of them by itself can optimize the entire operation. The common lesson they offer is that the industry has already built the technical "pieces" of automation; it is the orchestration layer that is missing.

4.6 Vision-Based Safety and Monitoring

Vision-based safety monitoring, an underdiscussed dimension of drilling automation is its role in safety management and operator environmental, social, and governance (ESG) performance.

There has been significant development of "machine watching the driller" to help improve HSE performance. Vision systems demonstrate that automation can be leveraged not just for rate of penetration or non-visible lost time, but directly in support of crew protection or enforcement of HSE performance. A very common use case is red-zone monitoring, with cameras and AI-based video analytics providing alerts and even interlocks when workers enter a designated safety zone.

Nabors' SmartROS automation system, for example, features a red-zone monitoring function where pipe-handling equipment are automatically stopped if an operator enters a red zone (Roberts, Flin, Millar, & Corradi, 2021). The International Association of Drilling Contractors (IADC) has published a good overview of vision-based automation, with specific recommended practice (RP) and guidance on using it for red-zone management (IADC, 2016; Rockwell Automation, 2025).

Automation applied in this way to very strictly enforce safety barriers has the potential to greatly reduce the probability of serious injury and fatalities. Vision monitoring is also being applied to other, more specialized applications. Cameras at the shale shaker, for example, can be used to recognize overflow and blinding conditions that, if left uncorrected, can lead to inefficient solids removal or unplanned releases to the environment. Mud pit cameras provide another source of redundancy for early kick and loss detection, with visual evidence that fluid volume is increasing or decreasing. Machine vision on catwalks and pipe decks is also being used to track pipe-handling motions to avoid dropped objects or unsafe equipment positions. Each of these examples are more specific, and can be use cases for the additional redundancy. All provide, by visual monitoring, a complementary for other sensors to increase overall reliability, and enhancing overall performance.

In this way, cameras are not only used for surveillance but can also be used to augment cognition and human decision making. Vision systems also have another important layer of value for operators, which is beyond risk reduction and moves into important audit trails and documentary evidence of compliance. This can be of value to regulators and insurers, so video recordings of automated safety enforcement and anomaly detection can provide useful supporting evidence when operators need to show regulators that they are ALARP compliant. This provides both reputational and very real financial incentives to operators to invest in these systems.

In summary, vision-based monitoring represents a very important but sometimes underappreciated dimension of drilling automation. By using cameras and AI-enabled vision analytics, operators can use automation not just for downhole optimization but also to protect crew and improve ESG performance. These systems help to illustrate that automation is not just multidimensional, but also multidirectional: not just drilling faster or cheaper but also drilling safer and with a higher social license to operate.

4.7 Cross-Case Analysis

Key insights from the cross-case analysis are as follows:

Drilling automation succeeds when adoption is staged and gated; incentives and enablers (aligned, timely, robust communications/data and governance with clearly defined roles and responsibilities) for change are provided; and a cultural shift is supported by standards, third-party open architectures and hubs to enable interoperability and plug-in technology adoption.

Projects that demonstrate benefits of stage-wise progression and operator–contractor co-design include BEACON (Thorsen et al., 2013), Hess–Nabors (Gillan et al., 2018) and Equinor's orchestration pilot (Millward et al., 2025), which also underscores the roles of arbitration and training.

Bounded autonomy within prescribed boundaries can be achieved and has demonstrated value, while autonomy on an industry level or rig-wide level remains largely elusive. The building blocks of the Rig Brain (ROCs, twins, predictive models, edge AI, vision systems, etc.) are in place, and well-proven in the industry with unnegotiable positive effects, but are still fragmented, with a need for Rig Brain as a unifying architecture.

Chapter 5. The Missing Link: Rig Brain

5.1 Definitions and Origins

Drilling automation has progressed over the past two decades as a series of notable advances, each of them significant within their own domain, but without convergence across systems. ROCs centralized subject matter experts, and allowed one team to monitor multiple rigs simultaneously (Thorsen, Sæverhagen, & Dagestad, 2013). NOVOS, LOGIX, DrillOps, and other vendor solutions automate discrete workflows or optimize specific variables (NOV, n.d. [Ref #29]; Halliburton, n.d. [Ref #17]; SLB, 2023). Potential failures are identified by predictive analytics and anomaly detection models identify potential failures before they become critical (Liu et al., 2025) Managed Pressure Drilling (MPD) has proven that automation can operate safely in narrow pressure envelopes (World Oil, 2021). in addition to the Closed-loop trajectory control systems, which have demonstrated bounded autonomy by landing wells within meters of their planned destinations (SLB, 2024; Journal of Petroleum Technology, 2024).

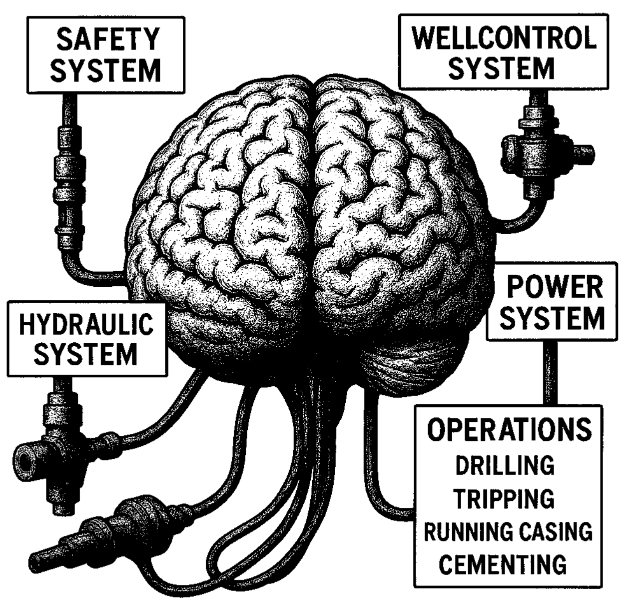

Figure 5: Rig brain visualization

All of these technologies have some form of proof of concept that automation works. When considered collectively, however, the industry has developed a patchwork architecture of islands of excellence that do not work together. Systems are siloed in their vendor's proprietary architecture, they are optimized around narrow key performance indicators (KPIs), and they are rarely connected to the operator's high-level goals. The result is a fragmented, inconsistent, and therefore difficult to scale automation ecosystem (Millward et al., 2025). Rig Brain was developed to fill this gap. The initial definition of Rig Brain is a vendor-neutral orchestration layer that is operator-owned and -governed. Rig Brain's purpose is to converge four key elements: sensing, data integration, decision logic, and execution. By integrating these threads into one architecture, Rig Brain enables system-level intelligence that aligns the performance of subsystems to overall drilling objectives: safety, efficiency, well integrity, and environmental stewardship. The biological metaphor between the human and rig brain is intentional. Just as the human brain consolidates information from vision, hearing, and touch, and compares it to memory, then issues coordinated motor commands, the Rig Brain serves as the "central nervous system" of the drilling operation - this is what we aim for - a sysmtem of systems. It does not micromanage individual subsystems; rather it orchestrates them, providing high-level direction while leaving the execution of specialized tasks to each vendor system (Cao et al., 2024; Energistics, 2025).

Framed in this way, drilling automation can be considered a system-of-systems problem. Each technology — MPD, geosteering, tripping automation, fluids optimization, predictive maintenance — can be thought of as an "organ." Alone, each works well, but without a nervous system to coordinate them, they are unable to work together. Rig Brain is that nervous system.

This concept is closely related to the integration gap. The origins of this idea can be traced to Equinor's 2025 multi-vendor orchestration pilot, which proved that the bottleneck is not in technical capability but in the absence of arbitration and governance between subsystems (Millward et al., 2025).

In addition, De Wardt and Cayeux, writing for the SPE Drilling Systems Automation Technical Section, have long argued that drilling automation is inherently a multi-agent problem that requires coordination between the different subsystems which are often optimized towards conflicting KPIs (de Wardt et al., 2024).

We see the same observations in the DSATS technical framework papers, which identified arbitration and interoperability as the missing building blocks between advisory tools and autonomous operations (de Wardt, Sheridan, & DiFiore, 2016; Macpherson, Cayeux, Thorogood, & King, 2013). It is also worth noting that the industry is not the first to have faced this problem. Other capital-intensive industries have made this leap.

Marine operators have had a history of successfully combining dynamic positioning, propulsion and safety systems under single control architecture demonstrating that vendor-neutral orchestration is technically possible in extreme, safety critical environments. While knowing that drilling operations is a much more complex from ship-positioning system, nor these systems have not been designed to directly control drilling processes, but for vessel station-keeping and marine safety, they do provide a proven baseline that multi-vendor integration can be reliable under offshore conditions (World Oil, 2021; Millward et al., 2025).

in addition, Manufacturing's migration into Industry 4.0 demonstrated how vendor-neutral orchestration, a harmonic seemless production, built on standards like OPC UA and IEC 62443, allowed robots, sensors, and control systems from multiple suppliers to work as one (International Society of Automation, n.d.[ref #23]; OPC Foundation, 2025; Rockwell Automation, 2025).

These examples show that orchestration, or a system of systems, is not a speculative concept — and it is indeed what is missing as the stepping stone towards automation - an established path towards achieving safety and performance objectives in complex domains. Taken together, this frames Rig Brain as both a conceptual advance and a practical necessity.

Conceptual, because it reframes the approach to drilling automation as a system-of-systems that can only be effective if orchestrated.

Practical, because operators are now under increasing pressures that can't be solved by islands of excellence alone: new regulations requiring safety and ESG performance, an ongoing cost discipline in increasingly volatile markets, and the demographic pressures of replacing an aging workforce (Arndt, Hoffart, & Gabrielsen, 2025; Macpherson et al., 2013).

In short: Rig Brain is the next step in the evolution of drilling automation. It is the transition point from a set of discrete automation tools to a cohesive orchestration framework that can be scaled across fleets. The technology is here. The standards are here. And other industries have already proven it can work reliably. What is missing is the operator-led initiative to pull it all together into a system that behaves as one.

5.2 Critical Enablers

The Rig Brain is not a product. It is not a black-box solution from a vendor. It is an architectural principle. In particular, it is the recognition that Rig Automation needs to be built from four interdependent components: sensing and acquisition, data integration, decision logic, and human–machine interaction. Each of these four exists today in rudimentary form. The challenge is not creating them from scratch. It is stitching them together into a coherent, operator-owned system.

5.2.1 Sensing and Acquisition

Drilling automation starts with data. Without high-resolution and high-reliability data feeds from the rig floor and the downhole environment, no higher-level coordination and orchestration is possible. As a result, over the years the industry has pushed hard to increase the amount and speed of data acquisition. Wired drill pipe and systems like TDE Powerline have moved telemetry rates well past 200 kbps, making mud pulse [F6] obsolete by comparison (TDE Group, n.d. [Ref #49]). Vibration, pressure, and gamma-ray data can now flow near real-time downhole for purposes of geosteering and vibration management. Instrumentation on the surface is also becoming more sophisticated. Measurements of torque and drag, fluid properties from automated pit sensors, vibration monitoring from surface accelerometers, continuous health tracking of equipment.

5.2.2 Data Integration

If sensing is the “eyes and ears” of Rig Brain, then data integration is its “spinal cord", so data integrations is viewed as the connecting tissue through which signals from various domains pass and are normalized. On this front, and with integration the drilling industry has seen tangible advances. Over the past decade, WITSML has emerged as the main industry standard for wellsite data exchange (Energistics, 2025) – not in an official or legal sense, but in practice, everyone uses it as if it were the standard. It provides a semantic infrastructure that vendors can use to consistently describe drilling data. Meanwhile, OPC UA has established itself as the standard of choice in industrial automation more broadly. It is platform-agnostic, secure, and built for real-time, low-latency communication (International Society of Automation, n.d. [Ref #23]; OPC Foundation, 2025). In edge-constrained scenarios like offshore rigs, MQTT is also prevalent for lightweight communication [F06]. Each of these standards has its strengths. WITSML is superb at representing domain-specific drilling data: well trajectories, mud logs, operational reports, etc. On the other hand, if we require a more rubost error handling and role-based acess control, then OPC UA - another integration standard - was architected for reliability and cybersecurity (International Society of Automation, n.d. [Ref #23]; Rockwell Automation, 2025). But this also created a conflict. WITSML is often too cumbersome for real-time control scenarios, while OPC UA has lacked drilling-specific semantics. Recent pilots are starting to break through this impasse. Energistics and the OPC Foundation, as well as a vendor-neutral group in Europe, have demonstrated WITSML and OPC UA can be made interoperable: WITSML takes care of the semantics, while OPC UA provides the secure, low-latency transfer (OPC Foundation & Energistics, 2025). The hybrid result allows drilling-specific meaning to coexist with industrial-grade robustness and security. For Rig Brain, this hybrid fabric is non-negotiable. Without common standards and gateways, orchestration reverts to brittle, vendor-specific “handshakes” that are costly to maintain and prone to failure. The integration layer is what ensures Rig Brain can “speak the same language” at all subsystems, no matter who supplies them.

5.2.3 Decision Logic

Data is not value, of course. The real value is in the actions you take as a result. But what distinguishes Rig Brain is the decision logic layer, which takes in multiple recommendations and decides how to act at the system level. Today’s vendor platforms provide very sophisticated but siloed control. NOVOS can automate a drilling sequence. LOGIX can provide trajectory optimization in real time. DrillOps can aggregate and supervise workflows (NOV, n.d. [Ref #29]; Halliburton, n.d. [Ref #17]; SLB, 2023; SLB AI Blog, 2022 [Ref #47]). Each is impressive in its own right. But each also optimizes within the boundaries of its own domain. This leads to the situation De Wardt and Cayeux [F13] described as “optimization myopia” where subsystems do their jobs very well but inadvertently work against one another. (de Wardt et al., 2024)

Rig Brain introduces a meta-level arbitration layer. Its job is to ingest inputs from multiple advisors—geosteering suggesting higher ROP, MPD recommending higher backpressure, predictive maintenance advising lower RPM, and so on—and arbitrate on what actions to take across the system. Arbitration is not random. It is not algorithmic self-referential; it is guided by explicit operator-set priorities: safety > integrity > quality > efficiency (Accenture, 2022)

For example, if geosteering and MPD give conflicting instructions, Rig Brain would work towards or on the side of maintaining wellbore pressure integrity before optimizing the trajectory. Another dimension is time scale. Decisions can be fast or slow. Safety interlocks may have to trigger in milliseconds. Parameter adjustments take seconds. Trajectory planning takes hours. Rig Brain logic must accommodate all these scales to ensure there is coherence between short-term and long-term decision horizons.

This logic is not theoretical. Equinor’s 2025 orchestration pilot [F06] showed that arbitration algorithms can prevent conflicting outputs from vendor advisors from paralyzing crews. Instead of humans being put in the position of having to choose between clashing recommendations, Rig Brain would do that upstream and present the crew with a single, coherent set of actions (Millward et al., 2025).

5.2.4 Human–Machine Interface

The final piece is the human–machine interface (HMI). No orchestration system can be successful if operators do not trust it. This is the point of the research on Human Systems Integration (HSI) which has been a core theme of Equinor's automation work. In particular, studies on alarm management, screen and GUI design, and human factors have shown that automation must reduce cognitive burden, not increase it (Arndt, Hoffart, & Gabrielsen, 2025; Roberts, Flin, Millar, & Corradi, 2021).

Equinor's driller cabin human-factors research, conducted as part of their own cabin redesign project, demonstrated the risk levels (Arndt, Hoffart, & Gabrielsen, 2025). Alarm fatigue, screen clutter, and poor ergonomics were all proven to directly and adversely affect situational awareness. For Rig Brain to succeed, it must find a way to present information to crew members that aids rather than hinders.

Wehn looking at the human-machine interaction, we would expect for a Rig Brain to be capable to Synthesize and filter, or fuse in, information into meaningful and situationally aware context, not just raw data feeds. Deliver prescriptive recommendations with justifications and confidence bands, such that operators understand not just what the system is recommending, but why it is recommending that action. Clearly communicate the boundaries of its authority, where automation is in control, and where it is seeking human confirmation. Allow rollback to advisory or manual control at any time. This last principle is critical. Rollback is the fail-safe of automation. It must be allowed at any time. This is the only way to ensure automation never creates an unacceptable risk to safety or operator confidence. If a model drifts, or data quality degrades, crews must be able to reassert manual authority at any time, instantly. By internalizing these principles, Rig Brain creates a true partnership between human and machine. Operators are always in the loop but no longer overwhelmed. Automation provides recommendations and can execute within agreed-on boundaries; humans retain ultimate authority. Trust is built not by replacing people but by empowering them with much clearer, much more reliable information. The four components of this section demonstrate that Rig Brain is not a technology that has yet to be invented. What Rig Brain adds is the architecture to connect these components into a coherent, operator-owned framework. The value of that architecture is not in replacing the vendor systems but in coordinating them. Each vendor continues to innovate in their own domain. Rig Brain just ensures that their contributions all serve operator objectives. Without it, automation is fragmented. With it, drilling gets a true nervous system capable of coherent, scalable performance – a true steppingstone towards full automation.

5.3 Why Current Vendor Models Fail

Vendor Vendor automation has delivered powerful tools at solving problems in their own silos, but the sum of these systems has rarely amounted to whole-rig optimization. The root problem is structural. Subsystems are engineered to solve their own objectives – whether that be trajectory accuracy, hole cleaning, or pressure control – and so each performs well locally. But without a layer of arbitration, these systems can easily work at cross-purposes. Progress at the local level can fragment in the system level.

Then there is the problem of data. Operators often lack full control over the data generated on their rigs. Service contracts with vendors often give ownership of the data to vendors or restrict its use, locking out benchmarking and fleet-wide learning. "The "broken model" means the party that is on risk and on cost of drilling, actually gets locked out of its own memory banks." (Drilling Contractor, 2017; SLB, 2024 [Ref #43]; Journal of Petroleum Technology, 2024) Integration is fragile, even with access to data. Proprietary formats and closed APIs make systems difficult to align, and without shared definitions or conformance testing, brittle integrations will tend to fail in the field (International Society of Automation, n.d. [Ref #23]; OPC Foundation, 2025).

Finally, there is the problem of incentives. Day-rate and service contracts pay for utilization, not for efficiency, so a contract that doesn't pay for it has no incentive to make sure their system plays nice with others (Schlumberger & NOV, 2021). All these factors combined explain why we have lots of capable automation “pieces” but not enough of the coordinated performance we need. Until orchestration changes the rules, the whole will remain less than the sum of its parts.

5.4 Cross-Industry Precedents

Drilling is not alone in needing to get these automation systems to play well together. Other industries that are equally high-risk and capital-intensive have been faced with this orchestration challenge and have already found solutions. It’s instructive to look at those to see what can and cannot be adapted to drilling.

Consider, for instance, maritime automation. Offshore vessels, particularly drillships and semi-subs, are dependent on dynamic positioning (DP) systems to hold station. They are not a single-vendor system. Instead, thrusters and propulsion control systems, GPS, gyros, environmental sensors, and more are all integrated to make a DP system from multiple vendors. These systems run under an integration layer owned by the operator, with redundancy and safety logic written on top. DP must also interoperate with other vessel systems, such as ballast control, power management, and other marine safety functions. The upshot is a single unified control environment with different vendors still providing their own equipment but being required to interoperate. The lesson is obvious: multi-vendor orchestration is not a hypothetical situation. It has been de rigueur in the maritime world for years, and it has been proven out in harsh offshore environments (World Oil, 2021; Millward et al., 2025).

A second example is the ongoing Industry 4.0 transformation in manufacturing. A smart production line today can include robots, sensors, and quality-control systems from many different suppliers. The common denominator among these is not one vendor that owns the entire stack but common standards such as OPC UA for data exchange and IEC 62443 for cybersecurity (International Society of Automation, n.d. [Ref #23]; OPC Foundation, 2025; Rockwell Automation, 2025).

Such standards ensure that components “speak the same language” and that operators can be confident that systems are secure. Critically, these rules do not inhibit vendor innovation. Each supplier still develops its own specialty tools, but they must fit into a standardized and interoperable architecture that the operator controls. These examples matter for drilling because they show two things. First, that vendor-agnostic orchestration is technically possible and has already been demonstrated in safety-critical environments.

Second, that this orchestration can be more effective than the alternative of fragmentation and single-vendor solutions. The parallels are not perfect—the geologic uncertainty of drilling distinguishes it from a factory floor—but the pattern is suggestive. If ships and factories can orchestrate complex operations reliably across multiple vendors, there is no fundamental reason why rigs cannot do the same. The difficulty is not one of technical possibility, but of will: the willingness to use common standards and governance structures that can make integration work in practice.

5.5 Rig Brain as an Operator-Owned Orchestration Framework

The Rig Brain is perhaps better thought of not as another vendor product but as an operator owned middleware platform. The role of Rig Brain is to sit between the numerous subsystems already installed on a rig and to tie them together through standard interfaces and to apply governance of data, security and decision logic. In this way the somewhat ad-hoc set of tools the industry has cobbled together over the years becomes orchestrated - taking the scattered tools the industry has developed and turns them into a coordinated whole.

5.5.1 Architecture

The architecture is layered. At the base is the sensing environment. This is where data is ingested and, to a first degree, filtered and preprocessed. It is a intersection or junction of surface instrumentation, downhole measurements, wired drill pipe, and increasingly, AI-based preprocessing at the edge. Systems like TDE Powerline already deliver the bandwidth necessary for this role TDE Group, n.d. [Ref #49] ; Bimastianto et al., 2020).

Sensing is supported by the data fabric layer. This is where high-frequency measurements are made interoperable. It structures drilling-specific data using WITSML, ensures secure, platform-independent communications with OPC UA, and guarantees performance at the edge with MQTT where bandwidth is limited International Society of Automation, n.d. [Ref #23]; OPC Foundation, 2025; OPC Foundation & Energistics, 2025). The digital twin and process-state engine are the integrative model of the system. This is where live operational data is mapped against planned states with uncertainties quantified and transitions defined.

By maintaining a real-time representation of the well and rig, Rig Brain can support coordination and arbitration (Cayeux et al., 2024; Cao et al., 2024). The arbitration and policy core is above this, the heart of the Rig Brain. It receives recommendations from subsystem advisors, applies operator-defined priorities and constraints, and enforces them. In doing this, it ensures conflicts are resolved before they get to the driller and that safety envelopes are always respected (de Wardt et al., 2024; Accenture, 2022). The human–machine interface is the point where orchestration meets the crew. It must present fused and filtered data, the reasoning behind recommendations, confidence levels, and give operators the ability to override or rollback to manual modes at any time (Arndt, Hoffart, & Gabrielsen, 2025; Roberts et al., 2021).

Finally, the governance layer runs across all others. It enforces cybersecurity aligned with IEC 62443 and IADC guidance, requires model validation and rollback options, and ensures all actions are logged through audit trails (International Society of Automation, n.d. [Ref #23]; OPC Foundation, 2025 ; IADC, 2016; Rockwell Automation, 2025; Goodkey et al., 2024).

5.5.2 Core Functions

The Rig Brain augments with functions that no vendor platform could (individually) supply. The first is to be a multi-advisor arbitrator, arbitrating competing inputs and reconciling their differences based on priorities the operator sets. This would otherwise leave optimization trapped in silos. The Rig Brain also bounds the solution space to ensure drilling always operates inside specified safe envelopes for pressure, torque and drag and BHA limits. It is to prevent automation optimizing for some notion of efficiency in a myopic way that sacrifices these boundaries. The third key function is degradation path management. As confidence in data or models degrade, the Rig Brain must degrade gracefully from execution to advisory to manual modes without making unsafe or confusing handovers (Millward et al., 2025 ; Accenture, 2022). The platform also secures data rights, so operators can have data sovereignty and control of the operational record while not infringing upon vendor intellectual property rights (Drilling Contractor, 2017; SLB, 2024; Journal of Petroleum Technology, 2024). In parallel, it secures cybersecurity by design, constraining and monitoring operator access through role-based access, intrusion detection and response so operations can be proven secure (International Society of Automation, n.d. [Ref #23]; Rockwell Automation, 2025). Transparency is by design: every model is required to have a documented scope, assumptions and validation record and every automated decision results in an audit-able trail of breadcrumbs (International Society of Automation, n.d. [Ref #23]; OPC Foundation, 2025 [Ref #30]; Roberts et al., 2021 [Ref #34]). Finally, Rig Brain can be designed to perform with adaptive autonomy where an operator can tune the process to different levels of automation based on the state of the process, their confidence in models and their risk appetite (Arndt, Hoffart, & Gabrielsen, 2025; Roberts et al., 2021).

5.5.3 Commercial and Regulatory Model

Technology alone will not make Rig Brain possible. Adoption is also a function of how operators contract and how regulators accept governance practices. Service contracts need to explicitly require data sovereignty and open export rights (SLB, 2024; Journal of Petroleum Technology, 2024), require adherence to interoperability standards like

WITSML and OPC UA (International Society of Automation, n.d. [Ref #23]; OPC Foundation & Energistics, 2025), and state vendor lock-in protection explicitly (TDE Group, n.d. [Ref #49]; World Oil, 2021). Regulators must be ready to accept audit trails, model validation and rollback protocols as verifiable components of safety cases (de Wardt, Sheridan, & DiFiore, 2016; IADC, 2016). Otherwise, orchestration is at risk of becoming a technical triumph and commercial and regulatory orphan.

5.5.4 Implementation Roadmap

Rig Brain cannot be switched on overnight. Like other industries, it requires a staged transition. In the first stage, it would operate in an advisory role, monitoring multiple subsystems, running arbitration, and recommending actions. In the second, it would progress to bounded execution, automating specific workflows but always with rollback to manual control. In the third stage, it would handle full orchestration, arbitrating across vendors and functions. Only in the final stage would it scale to fleet-wide deployment, allowing learning loops and cross-project benchmarking. This roadmap mirrors the paths seen in maritime and manufacturing, where trust, governance, and regulation were allowed to mature alongside technical capability.

The Rig Brain provides that framework. By combining sensing, data integration, arbitration, human oversight, and governance, it allows operators to coordinate vendor systems according to their own objectives rather than those of individual suppliers. In doing so, it transforms today's patchwork of isolated technologies into an orchestrated whole. The Rig Brain is not the end state of drilling automation, but it is the critical step that will allow the industry to move from bounded autonomy to scalable, repeatable, and safe fleet-wide automation

Chapter 6. Data, Governance, and Cybersecurity

The value of any Rig Brain orchestration architecture or framework is not a technical consideration. The bigger concern is around the ownership of the data, how the data is governed and controlled, and how cybersecurity risks are handled and trust is built between humans, machines and regulators. Until these issues are clearly addressed, a technically elegant automation architecture is at risk of underutilization or outright rejection. This chapter will consider four critical dimensions. The first is data ownership and sovereignty. The second cybersecurity issues in multi-vendor edge and cloud environments. The third is the governance framework for a trusted automation architecture and the fourth is what the regulators need to change to allow and encourage adoption.

6.1 Data Ownership and Sovereignty

One of the most long-standing discussions on automation in drilling has been around data ownership. This seems like a simple issue: the operator pays for the well, owns the risk, and by all rights should own the records. In reality, contracts may be written to give vendors wide latitude over how data are used.

For example, service providers may place restrictions on how data may be accessed, exported, or shared. There are even cases where vendors retain exclusive rights to the datasets created as their equipment is being used. This means they are in possession of important information that is in effect being held “hostage.” This has been referred to as a broken model, since it places the stewardship of a system in different hands from the entity that must answer to regulators, shareholders, and the community for it. Operators have little ability to build institutional memory or perform independent analytics without full access to their data (Drilling Contractor, 2017).

A more commonly held view now is that a line needs to be drawn between operational data and intellectual property. Raw facts, such as measurements and drilling parameters, well logs, and key performance indicators should be the full property of the operator. Vendor specific algorithms, workflows, or methodologies for analytics may remain proprietary.

This split allows the operator to have sovereignty over operational memory, while vendor innovation can be recognized and protected. The concept of data sovereignty also has other ramifications. It is a necessary condition to building systems of knowledge for the long-term.

For example, in Equinor's digital transformation efforts, a key objective was the creation of common repositories of learnings that could be captured across multiple campaigns. Without sovereignty, this level of benchmarking and cross-learning is not possible. Sovereignty has a direct bearing on the Rig Brain vision. Real-time access to data streams from all subsystems is essential for achieving the projected high degree of orchestration (Millward et al., 2025).

6.2 Cybersecurity Risks in Multi-Vendor Environments

If sovereignty is the foundation of trust, cybersecurity is the custodian of it. The additional vulnerability that automation brings is the fact that there are ever more connections between systems and subsystems, and far more often than not, these span across vendors. The more telemetry streams or API calls or edge AI models you have, the bigger your attack surface is. In some of my previous articles, I've already touched upon how the seemingly unstoppable appeal of distributed control architectures has also made them susceptible to a larger number of infiltration channels. IEC 62443 is the gold standard for hardening industrial systems, going into granular detail about how to implement network segmentation, authentication, encryption and incident response (International Society of Automation, n.d. [Ref #23]; Rockwell Automation, 2025).

These standards have also been translated by the International Association of Drilling Contractors (IADC) to the more particular use cases of rigs, where mobility and the hostile physical environment and the higher number of third-party vendors have historically resulted in lacking security practices (IADC, 2016 [Ref #21]). Good practices around safeguards are also slowly starting to crystallize. Networks need to be segmented so that, for instance, a vulnerability in the mud-logging system should not be able to propagate itself to control domains. Role-based access needs to be enforced between vendor systems, limiting the risk of unauthorized personnel, for example, making configuration changes. Intrusion detection and anomaly monitoring should be implemented as much as possible at the edge as well as in centralized control.

Above all, incident response processes have to be designed for operational environments in which downtime is not an option. If a factory line can be turned off for a few hours while a cyber issue is remediated, a rig cannot (International Society of Automation, n.d. [Ref #23]; IADC, 2016 [Ref #21]). Saudi Aramco's edge AI deployments are a case in point. Controls around governance were built into the solution itself from the ground up with model validation and staging before deployment, secured pipelines for updates and fail-over plans in case of an outage or suspected compromise. As is true with many facets of cybersecurity, another example of how cybersecurity has to be part of the orchestration architecture rather than an afterthought (Alanazi, Altuwaijri, Bagabas, Khan, & Otaibi, 2025).

6.3 Governance Frameworks

Beyond ownership and security there is a broader governance question: how do operators ensure automation remains robust, transparent and accountable over time? A key requirement for that is model validation. Predictive models and optimization algorithms all drift as conditions change. Unless they are continually validated and recalibrated, trust quickly erodes. Equinor's early automation experience showed how crews would simply start overriding recommendations when they no longer saw the models as accurate (Arndt, Hoffart, & Gabrielsen, 2025 [Ref #15]).

The Rig Brain concept tries to build governance into the architecture through "model cards" that document the scope, training data, known limitations and validation status of each model. Audit trails are also crucial. Every automated decision, input data, override and outcome should be logged. These logs are important not only for internal learning but also for evidence in front of regulators or insurers. Auditability is important for reassuring stakeholders that automation is not a black box but a transparent process open to review (International Society of Automation, n.d. [Ref #23]; OPC Foundation, 2025 [Ref #30]). Another key to governance is rollback capability.

Automation should never be allowed to exceed the level of trust that operators have in it. If data quality or model confidence erodes, the system needs to gracefully roll back to advisory or manual control. This notion of adaptive autonomy was raised in the HSI studies as well where operators emphasized the need to always know exactly when automation was in control and how to wrestle it back (Arndt, Hoffart, & Gabrielsen, 2025 [Ref #15]; Roberts, Flin, Millar, & Corradi, 2021 [Ref #34]).

6.4 Regulatory and Compliance Considerations

Finally, and perhaps most importantly of all, no orchestration framework can be effective unless it is also codified in the regulatory domain. Much of the current regulatory regime for drilling operations was written with manual modes of operation and human supervision as the frame of reference. Regulators will need to find a way to adjust to allow for safety and yet remain technology agnostic and avoid the temptation to offer narrow technical solutions. Outcome-based regulation is one path. Instead of regulating the detailed design of automation, regulators can shift their focus to requiring evidence that safety, environmental and performance objectives are demonstrably met. Audit logs, rollback systems and model validation are examples of the sorts of mechanisms that can generate the evidence that regulators can then assess.

This is in broad terms the direction that safety regulation of aviation and maritime has already taken. Harmonization of regulation across jurisdictions is another important issue. Operators have to move across different regimes and fragmentation will act as a barrier to adoption. Industry bodies such as DSATS and IADC are already starting to produce guidance on interoperability and governance, and the next step is for regulators to accept orchestration governance as a factor in safety cases (de Wardt, Sheridan, & DiFiore, 2016; IADC, 2016). In conclusion, we think that regulation needs to move away from treating automation as an exceptional and essentially unpredictable mode of operation towards regarding it as normal provided that operators can demonstrate transparency, safety and accountability. If the conditions above are met – data sovereignty, embedded cybersecurity, transparent governance, and outcome-based regulation – the Rig Brain can become real. Otherwise it will be an attractive concept that remains on the margins of the industry. Implemented correctly it could be the architecture that finally brings safe, scalable and operator-controlled automation to the rig floor.

Chapter 7. Recommendations and Path Forward

The previous chapters have demonstrated that the technology building blocks for drilling automation are already available. Remote Operations Centers, digital twins, vendor platforms, edge computing, predictive models and vision-based safety systems have all been proven in the field. The missing link has been orchestration, an operator-owned framework like Rig Brain, that can bring these islands together into a whole. But technology by itself will not achieve the transformation. How the solution is adopted will depend on how operators, vendors, and regulators work through the challenges of data, governance and organization change. This chapter will provide a way forward, with recommendations specific to each group, and conclude with a roadmap for industry wide adoption.

7.1 Recommendations for Operators

The first lever of change available to the operators are data and orchestration architecture. Contracts must enforce data sovereignty. The operators own the data, and they should be able to use it however they want, instead of being constrained by a vendor platform. Vendor platforms must be contractually forced to use interoperability standards such as WITSML and OPC UA, and face penalties when failing to comply (Energistics, 2025; OPC Foundation & Energistics, 2025; International Society of Automation, n.d. [Ref #23]). Only when this foundation is in place can Rig Brain integration be made technically possible (International Society of Automation, n.d.; OPC Foundation, 2025; Drilling Contractor, 2017; SLB, 2024).

Second, however, are organizational and cultural enablers. The research conducted on the Psychological Technology Adoption Framework (P-TAF) has demonstrated that adoption will not be 100% technology-driven (Roberts, Flin, Millar, & Corradi, 2021). Rational reluctance to adopt (individual risk aversion, automation distrust, or fear of failure) can delay deployment much more than the shortcomings of the hardware or software. To counter this, the operators need to build trust, through transparent communication of the purposes of automation, clear rules for override, and visible demonstrations of system reliability. They should also identify internal champions who will model positive engagement with automation to the rest of the crew. Internal champions are well-respected individuals who can play an important role in transforming peer norms and breaking down skepticism. A fourth way in which operators can create a shift in the automation culture is to align incentives and performance measurement. In too many companies today, crews continue to be measured and paid against pre-automation targets and standards – the number of connections made per hour, the number of manual interventions, and so on. That sets perverse incentives for the crews to resist any move to automation. Measurement and incentive schemes must be realigned to new norms: rewarding crews that make good use of automation, override it when safety is threatened and contribute to continuous improvement. Organizations that seek to punish automation "mistakes" during the learning curve are unlikely to encourage learning, and will discourage adaptation when problems occur. Those that allow for controlled failure and reward demonstrated improvement are likely to build greater resilience and confidence (Accenture, 2022 [Ref #1]).

The third lever of change is workforce development. Training needs to be provided on more than the new system operation manuals. The workforce must also be prepared for human–automation collaboration: when to accept automation recommendations, when to question them, how to safely intervene when systems do not behave as expected. Training needs to be role-based and with an awareness that automation engagement is likely to be very different for the executive team, supervisors, drillers, and maintenance staff, among others. Cross-training and retraining of workers will help avoid dependency on a few experts. Continuous learning systems will also need to be put in place, including both formal training but also mentoring and forums for discussing new challenges and problems, to keep pace with the evolution of technology (Accenture, 2022).

The last recommendation for operators is to embrace automation, but not to do so half-heartedly. Pilot programs must be well thought through, with clear goals and metrics for results, with knowledge-sharing and learning processes put in place from the start. Crews and teams chosen for pilots must be well-balanced and include both the natural advocates and some self-identified skeptics – in order to avoid resistance to change being discovered too late in the process, and solutions not being accepted by the doubters. Failures in pilots must be shared and studied rather than hidden away; nobody learns if nobody is willing to talk about mistakes. Automation systems can be adopted incrementally, and there are no entry points that have not already been tried by someone. Advisory systems like ROCs and trip speed optimizers are comparatively low-risk first steps to take on automation and get automation value on rigs today (Thorsen, Sæverhagen, & Dagestad, 2013; Baker Hughes, 202; Energistics, 2025).

7.2 Recommendations for Vendors

The main message for vendors is to think of interoperability as an opportunity, not an existential threat. Vendor lock-in certainly helps defend the bottom line in the short term but it's not based on trust and greatly reduces the willingness of others to use and adopt these tools. Vendors that open up and make available open, standards-based interfaces will find it far easier to partner with operators that are creating orchestration stacks (OPC Foundation, 2025; OPC Foundation & Energistics, 2025). That said, Rig Brain doesn't make "best in class" vendors irrelevant. Rig Brain doesn't replace specialized systems; it coordinates them. Best in class geosteering, MPD, anomaly detection, or surface automation tools will always be in demand.

The essential requirement is vendors build their tools to be interoperable and based on vendor-neutral foundations (NOV, n.d. [Ref #29]; Halliburton, n.d. [Ref #17]; SLB, 2023). Vendors also have a responsibility for knowledge transfer. One of the reasons that automation projects go bad is that the operator is reliant on the vendor for knowledge in order to implement the technology, but has very little capability after the contract ends. As such, vendors should be mindful that partnerships for digital automation include time-bound structured training, documentation, and joint operations during the initial go-lives. Long term co-marketing and co-sourcing deals that outlive the procurement process are a useful mechanism to ensure sustainability and safeguard the investment (Gillan, Isbell, & Visitew, 2018; Millward et al., 2025).

Finally, vendors must understand that trust and transparency are valuable commodities. Operators want to know why algorithms make the decisions that they do, so vendors should have a good explanation for operators. This could take the form of opening up the black box, publishing validation data, or at least clean rollback functionality. Vendors that insist on being black boxes put themselves at risk of being left out of orchestration stacks that value accountability (Roberts et al., 2021).

7.3 Recommendations for Regulators

A deligate risk of missteps, or one risk of error in regulation and compliance is that regulators will oversolve for safety and environmental risks by creating artificial barriers to innovation. Much of the current regulatory framework was written for manual operations with an unstated assumption of 100% human supervision over all operations. As functions become automated, prescriptive technical requirements become less effective. The most productive regulatory model will be one focused on outcomes. Regulators need not tell companies how to build automation, but rather how to demonstrate it meets safety, environmental, and performance requirements. Audit logs, model validation records, and rollback systems all produce data of compliance with operational expectations. Elements of this logic are already in use, with regulators in aviation and maritime industries accepting automation as long as results are provably safe (de Wardt, Sheridan, & DiFiore, 2016; IADC, 2016).

Regulators will also need to harmonize requirements across jurisdictions. Many operators work in multiple countries, and the burden of effort to meet different requirements is a compliance burden. There is significant effort already ongoing in industry organizations such as DSATS and IADC in standards for interoperability and governance, but regulators should leverage that work to set shared expectations (Rockwell Automation, 2025; International Society of Automation, n.d. [Ref #23]). Finally, regulators will need to accept governance as a form of safety. Model validation, audit trails, and cybersecurity all should be accepted as contributions to a safety case. By codifying these requirements, regulators can reduce uncertainty while still providing operators with the flexibility to innovate (International Society of Automation, n.d. [Ref #23]; IADC, 2016).

7.4 Roadmap for Industry Adoption

It is unlikely that operators will ever shift directly to this level of adoption. A staged, gradual approach is much more likely, and has in fact been the process followed by many other industries that have arrived at a similar level. Each of these stages would approach that vision more closely, but with a narrower scope and set of guardrails: Stage one - Advisory orchestration: Rig Brain can monitor subsystems, run arbitration, and issue recommendations, but human operators are still in the loop for execution. This is a trust-building, low-risk phase. Stage two - Bounded execution: Rig Brain can execute selected, single-vendor workflows, subject to strong safety guardrails and clear rollback to manual control. Trip speed tuning, or automation of fluids monitoring/alerting are a few examples (Baker Hughes, 2021; Energistics, 2025). Stage three - Full, multi-vendor orchestration. This is the level we described above, where Rig Brain arbitrates between conflicting recommendations, and enforces system-level optimization. Vendors would still be responsible for, and own, their components, but an operator-owned, platform-level core component can orchestrate those vendors against each other (Millward et al., 2025; OPC Foundation & Energistics, 2025). Stage four - Fleet-wide rollout, with cross-rig learning loops: Standardization of orchestration across assets opens up opportunities for benchmarking, portfolio-wide optimization, and other gains. Negotiation of service contracts and vendor selection becomes easier, for example. This would be the analog of maritime DP or 4.0 manufacturing, where vendor-agnostic orchestration is not a differentiator but an assumption (Roberts et al., 2021; Accenture, 2022; International Society of Automation, n.d. [Ref #23]; OPC Foundation, 2025; Rockwell Automation, 2025). In any case, at every stage of this roadmap it is important that operators measure their performance and close the loop for continuous improvement. Expected outcomes would not just be the usual things like reduced ROP or NPT, but also measures of cultural buy-in, like trust in automation, adoption of training recommendations, and ESG impact.

Underinvestment in or misaligned incentives for those cultural measures are known to be significant roadblocks to otherwise-technically-viable automation efforts (Roberts et al., 2021; Accenture, 2022). Embedding some of ESG indicators (POB, emissions, resource intensity) directly would likely also help to build the business case, as those goals are a strong justification for automation, or such a leap towards it - it is the alignment of people, incentives, and governance. If those elements are in place, the Rig Brain concept can move from paper to practice, and can begin to deliver on its promise: A coherent system that transforms drilling automation from isolated successes into an integrated, industry-wide reality.

Chapter 8. Conclusions

The thesis has investigated the current and future state of automation in drilling and identified the need for a vendor-neutral orchestration of such an automation. It has further demonstrated that technology readiness is no longer a challenge. This state, however, also introduces challenges in governance, the organizational maturity of the operators and how they take ownership to control both data and integration.

Rig Brain was proposed as an operator-owned orchestration framework both as a theoretical progression and as a practical necessity. Theorizing on the path forward through practical theory supported with economic motivators, success stories and cross-industry examples.

8.1 Key Findings

8.1.1 Technical Feasibility and Proven Performance

The research confirms that the technical building blocks of automation are mature and field-proven. Autonomous directional drilling systems have landed wells within meters of planned targets with no incidents (SLB, 2024; Journal of Petroleum Technology, 2024). Edge AI deployments, such as those trialed by Saudi Aramco, have shown that complex machine-learning models can run directly at the rig site, removing latency and communication constraints (Alanazi, Altuwaijri, Bagabas, Khan, & Otaibi, 2025). Multi-vendor orchestration pilots, most notably the Equinor–Halliburton collaboration, demonstrate that open standards and arbitration logic can allow independent vendor systems to function within one integrated workflow (Millward et al., 2025). Taken together, these examples establish that drilling automation is technically feasible, safe, and increasingly sophisticated.

8.1.2 Economic Value Creation and Return on Investment

Case-based evidence provides additional support for the value of automation enabled by organizational capability. Trip speed advisory systems are used to reduce drilling times by more than eight hours per section without sacrificing safety (Baker Hughes, 2021). Automated fluids monitoring has been used to reduce the time to detect barite sag from six hours to 30 minutes, preventing costly stuck-pipe events (Baker Hughes, 2023) . Reported projects suggest that AI-enabled automation can reduce non-productive time by as much as 30 percent (Gillan, Isbell, & Visitew, 2018; SLB, 2023). The critical point to notice is that these gains are never automatic. They come into existence only when systems are put to work in organizations with the data integration, workforce training, and governance scaffolding in place to support them. The lesson is inescapable: Automation is valuable not as a stand-alone tool but in the context of an ecosystem of culture, incentives, and oversight.

8.1.3 Organizational Barriers as Primary Constraints

The technical and economic arguments for automation are strong. The greatest single class of constraints on automation remain organizational. The Psychological Technology Adoption Framework identifies risk aversion, low trust, and fear of failure as important adoption barriers (Roberts, Flin, Millar, & Corradi, 2021). Accenture's AI Maturity research tells a similar story. The research found that a mere 12 percent of surveyed organizations were "AI achievers." More importantly, the gap between high and low maturity organizations was "largely attributed to the availability of human capital to lead and deploy AI, not technology itself" (Accenture, 2022). The businesses that treat automation as a purely technical project – not as a change to culture, incentives, and governance – chronically underperform. We too discover that the human and organizational factors – not hardware nor algorithms – are the true bottleneck.

8.1.4 Governance and Risk Management Requirements

The final insight relates to the need for stronger governance regimes. Models used for anomaly detection or stuck-pipe risk prediction are often over-optimistic of their real-world performance due to leakage and poor validation practices. It is possible to have a model that passes laboratory metrics and fails in production if training and testing intervals are not contemporaneous or if some of the governance artifacts are not in place (de Wardt, Sheridan, & DiFiore, 2016; Liu et al., 2025).

Robust automation will require validation regimes that are bespoke to drilling such as model cards with variables and scope documented, leakage detection tests, and interpretability specifications, but these need to be integrated with audit trails, rollback procedures, and active monitoring. Absent this type of governance, the most sophisticated systems can quickly undermine operator trust and wider regulatory acceptance.

8.2 Managerial and Industry Implications

The challenge then for managers and executives in this space is clear. Automation is not about buying technology. It is about adopting a credible strategy that puts the technology in context of workforce transformation and vendor engagement.

There are three key aspects to this. First, it is about sequencing adoption. Advisory systems and ROCs offer an attractive risk-mitigated on-ramp that builds technical and organizational trust in the foundations of automation. From there a path can be charted through the automation of routine tasks, bounded autonomy in sensor-enabled closed-loop operations, and, finally, orchestrated multi-vendor systems overseen on an operator-owned platform. This phased approach both reduces risk and allows time for parallel evolution of governance models and organizational culture.

Second, automation is about workforce transformation. Operator training must evolve to address not just skills in using the systems, but also the cognitive and psychological aspects of human–machine teaming. This means crews need to be able to calibrate trust in the technology, sustain situational awareness, and maintain manual control skills as a contingency in order to recover from automation errors. Managing this change, though, must include active cultural change management to overcome the inevitable inertia and resistance. Visible leadership and alignment of incentives with expectations, along with open and honest communications, will all be essential. The risk, if this is neglected, is that new technology gets adopted technically, but not culturally. This, of course, leads to rejection and underperformance.

Third, successful adoption of automation will also require new types of vendor partnerships. Transactional vendor relations that are centred around procurement and cost minimization are not going to be enough in a world where orchestration of multiple offerings is required. Success will be more about long-term collaboration, shared risk and reward models, and vendor-neutral interoperability requirements. In particular, operators will have to take data sovereignty seriously and invest in developing vendor-independent orchestration platforms if they are to have any hope of avoiding lock-in. At the same time, they will also have to build technical capabilities of their own in order to remain in control strategically. This will make vendors that are open and transparent about their offering even more valuable, but the overall architecture needs to be designed and governed with the operator's interests in mind.

In conclusion, therefore, this is a challenge to those that manage operations, not just on technological fronts, but also on the organizational, cultural, and commercial ecosystems that are all interconnected. The Rig Brain offers a possible architectural solution. But it is leadership and governance that will make the difference in turning it into a reality.

8.3 Limitations of the Study

The results of the thesis are bound by the scope and methodology of the study. It considered drilling operations in traditional markets and mature infrastructural and regulatory environments. It excluded the analysis of unconventional, geothermal, and emerging-market applications. Therefore, the results and findings should be understood in context and should not be extrapolated beyond this. The thesis depended on published literature, including SPE papers, case studies, and vendor whitepapers. Published information can be subject to reporting bias and may not always reflect the full range of experiences, especially those that did not meet success criteria. Access to operational data was limited to public sources. This restriction affected the ability to analyze long-term performance and maintenance costs, as well as lifecycle economics. Temporal and technological constraints are also relevant.

Automation is an area that is rapidly changing and the developments in recent years related to artificial intelligence, edge computing, and digital communication technologies are tremendous. The scope of the thesis in terms of time period (2013–2025) might not be completely representative for the capabilities of technologies that existed before this period or the ones that will be developed in the future. Therefore, all the recommendations in this study are made based on the current systems and technologies which are expected to be further improved in the future.

The approach of synthesis also could not necessarily capture all of the subtleties of real field applications. Case studies presented in various publications were sometimes not reported with all the contextual details and, at the same time, access to real operational datasets could have allowed for a more detailed analysis of solutions' performance under different conditions and environments. These limitations may be overcome with original data collection and longitudinal studies in the future.

8.4 Future Research Directions

The next stage of research would benefit from evolving from pilots and case studies towards a systemic, long-term view of drilling automation. The following key areas stand out.

First, lifecycle analysis is needed. Tracking an automation system over years or decades can reveal patterns of degradation, reliability and maintenance requirements, as well as total cost of ownership (TCO). This can set realistic sustainability and value expectations for operators.

Second, relatedly, are longitudinal studies of organizational adoption. Following a project through several years, from early wins to mature operations, can reveal which efficiencies are sustained or lost, how crews build or erode trust, and how governance frameworks adjust over time. This evidence base would be critical for shaping not only staged rollouts, but continuous improvement.

Third, cross-industry comparisons are also needed. Drilling can benefit from more systematic study of maritime, manufacturing and aerospace automation. This could lead to lessons that refine integration strategies and governance frameworks for drilling. This research should include transferability across drilling environments, including unconventional and geothermal, to surface context-specific modifications.

Fourth, research should further develop the areas of governance and risk management. Adaptive frameworks for evolving AI-enabled systems should be designed, which tackle validation and auditability as well as resilience. Failure modes, recovery protocols, and human factors in crisis scenarios should also be investigated to improve operational safety and trust.

Finally, the research should begin to assess the strategic and economic implications of broad automation adoption, and not just at the project-level. Portfolio level impacts, shifts in service company business models, regulation, and international competitiveness should all be considered. Linking automation adoption to ESG outcomes and impacts—total emissions, safety, workforce footprint—will be important for investor and public trust.

Overall, the shift from disjointed tools to orchestrated systems will require not just the integration of sub-systems, but transformation of organizations, regulatory adaptation and strategic vision. Future research must provide the longer-term, cross-context, and governance-focused evidence to inform this.

8.5 Closing Reflection

In this thesis it was argued how the main barrier to drilling automation is not technical capability, but instead integration, ownership, and governance. The Rig Brain can point a way forward: a technology-agnostic, operator-owned orchestration framework that links the myriad technologies and toolsets that already exist into a cohesive system.

Once operators are willing to lead, vendors open up; regulators move to outcome-based oversight; and organizations shift investment from tools to culture and trust, then automation can move from a series of one-off successes to an industry-wide scalable standard. The opportunity is immense: safer operations, stronger ESG credentials, a place for drilling automation in the energy transition. The challenge is equally clear: without orchestration, the industry remains a quilted patchwork of disconnected tools and technologies. With orchestration, drilling can finally start stepping into full automation, unlocking the promise of automation as a technical, strategic, organizational, and social system.vendors willing to open up, regulators to shift to outcome-based oversight, and organizations to shift investment from tools to culture and trust, then automation can move from a series of one-off successes to an industry-wide scalable standard.

The opportunity is immense: safer operations, stronger ESG credentials, and a place for drilling automation in the energy transition. The challenge is equally clear: without such a coordination layer, the industry remains a quilted patchwork of disconnected tools and technologies. While with an orchestration, drilling can finally start stepping into full automation, unlocking the promise of automation as a technical, strategic, organizational, and social system.

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