

Integrating autonomy in mine rehabilitation: bridging technology and landform design

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Abstract

Earthworks in mine site closure is on the cusp of a transformative shift – from traditional, human-operated equipment to remote controlled, semi-robotic and fully automated machinery. The move to autonomous machines is well underway in the operational parts of mines all over the world with the use of autonomous haulage systems, however, the rehabilitation industry has not yet broadly adopted automation.

This paper explores how the technology currently employed in mine rehabilitation projects can be leveraged for a transition to automation, ensuring tomorrow's autonomous systems can deliver the desired landform outcomes.

Challenges faced for successful implementation are many and varied but this paper seeks to focus on the design and construction guidance inputs to the machines and systems. Complex designs often seen in mine closure such as geomorphic landforms can be difficult to construct due the steeper slopes, sharp valleys and varied material movement directions.

With autonomous machines there is no longer a human operator to make adjustments on the fly, so the design and guidance inputs need to be assessed for constructability and be able to be updated continuously throughout the project.

Through case studies and technical analysis, this paper will demonstrate how current technologies can lay the groundwork for the autonomous mine site closure strategies of the future and identify unique opportunities for autonomy to change the way we close mines.

By understanding and leveraging these tools, the mining industry can accelerate the safe, cost-effective adoption of automation in rehabilitation projects.

Keywords: mine closure planning, best practice, automation, efficiency, design optimisation

1 Introduction

Mine closure planning includes a broad range of activities such as tailings dam capping, infrastructure decommissioning, post-mining land use planning, and reclamation of pits and waste dumps. This paper focuses specifically on the bulk earthworks required for mine rehabilitation, particularly those involving bulldozers.

In Australia, large open cut coal and ore mines generate vast quantities of material that must be reshaped to meet closure compliance requirements. The scale of disturbance often makes bulk earthworks one of the largest single cost components of mine closure.

Across Queensland and New South Wales, over AUD 18 billion in rehabilitation liability has been calculated (Government of Queensland 2025; Government of New South Wales 2025). Our internal analysis indicates that 57% of this value is attributable to bulk earthworks, with bulldozers serving as the primary reshaping tool.

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While environmental goals and final land use outcomes are central to closure planning, the cost of material movement represents a key area for improving efficiency and reducing overall project costs. Optimising material movement, particularly through improved design and machine guidance, can unlock significant savings. These savings can be redirected to surface treatments such as topsoil placement, revegetation, long-term maintenance, or enhancements to final land use outcomes.

2 Why autonomy

Mine rehabilitation frequently requires machinery to operate in high-risk environments. Tasks include reshaping highwalls, traversing steep slopes, and capping water bodies or tailings ponds all of which require strict safety protocols. Removing the operator from the cab enables greater flexibility in work methodology and design implementation.

Between February 2022 and August 2023, there were 19 recorded bulldozer rollovers in Queensland coal mines alone (Brown 2025). While tele-remote systems can remove operators from high-risk environments, they increase capital and support costs without immediate productivity gains.

Introducing autonomous capabilities addresses these concerns by allowing a non-line-of-sight operator to control multiple machines, thereby increasing both utilisation and productivity.

Operator safety and comfort are improved, while the role of the operator evolves to include supervision, system management, and technology support.

3 Comparison: autonomous production versus rehabilitation operations

Autonomous haul trucks have achieved widespread adoption in large mining operations due to gains in safety, productivity, and cost efficiency. These trucks operate along fixed haul roads, making them ideal for autonomous control.

In contrast, autonomous bulldozer operations, particularly in rehabilitation, present a more complex challenge. Bulldozers continually modify terrain with each pass, working off design surfaces that often vary in slope, direction, and material properties.

For this paper, we reference Caterpillar's semi-autonomous tractor system (SATS), currently the only commercially available system that enables fully hands-off dozing during specific operations. The principles discussed apply broadly to semi-autonomous or fully autonomous dozing systems.

SATS, designed primarily for overburden dozing, allows a single operator to supervise up to four D11 dozers. However, the system is not fully autonomous. It requires human intervention in variable or complex conditions such as when encountering obstructions or executing fine trimming.

This highlights a critical gap. Haulage automation thrives on repeatability, rehabilitation requires adaptability, intelligence, and dynamic interaction with ever-changing terrain. Bridging this gap is critical for unlocking the next stage of cost-efficient and scalable mine closure solutions.

4 Challenges in constructing complex final landforms

On work sites with simple cut-and-fill designs, operators can perform efficiently with only basic height data. These designs often follow a linear alignment, such as road building or platform preparation where material direction is intuitive, and construction is straightforward. However, as mine closure projects shift toward more complex final landforms, especially those based on geomorphic principles, the task of determining where and how to move material becomes significantly more challenging.

In these cases, cut-fill heights alone are no longer sufficient for efficient execution. Operators are faced with interpreting intricate topography, drainage paths, and slope transitions, often without a clear directional reference. This increases the likelihood of inefficient dozing patterns, rework, and suboptimal material placement.

To address this, GPS vector guidance systems which provide both grade and directional push instructions have proven effective in reducing rework and improving construction efficiency, especially with introduction of natural landforms (commonly referred to as geomorphic designs). Operators can now receive not only the target elevation, but also the optimal direction to push material, which greatly enhances their ability to follow complex design intent.

Translating this capability into semi-autonomous systems such as Caterpillar’s SATS has shown promising results. Productivity improvements have been observed both in in-pit dozing and rehabilitation scenarios where vector data is available.

While there are numerous sites utilising remote control line of sight or tele-remote, these systems still rely on a single operator to run a machine. The new age of autonomous and semi-autonomous systems allows an operator to be removed from the cab and go hands-off for at least a short period of time. The blade load and machine speed are then entirely controlled by the dozer to remain within optimal range for efficient material movement. As of this writing, no fully autonomous dozer system is commercially available for mining class dozers capable of executing complex rehabilitation tasks. All systems still require the use of human operators for decision-making and manual control during complex operations such as trimming to final. However, if the efficiency gains seen in autonomous haulage could be replicated in dozer operations, especially when combined with vector control and intelligent design inputs, the potential to significantly lower operational costs in mine closure earthworks is substantial.

5 Guidance data and the design–machine feedback loop

For autonomous and semi-autonomous dozer systems to be effective in mine rehabilitation, they must operate with more than just static design models. They require a continuous feedback loop between the design, the machine, and the as-built surface data. This feedback loop allows the system to assess current progress, adjust future instructions, and maintain alignment with complex landform designs as conditions evolve.

In traditional human-operated systems, operators instinctively adapt to field conditions identifying hard ground, compensating for unexpected material types, or adjusting the push direction based on terrain features. Autonomous dozing systems lack this intuition and must instead rely on high-quality, dynamic guidance data to inform every movement.

The feedback loop begins with a digitally optimised landform design, often based on environmental requirements, drainage objectives, and volume balancing. This design is broken down into executable guidance data, including:

- cut-fill height targets
- directional push vectors
- material movement zones
- slope constraints and erosion control limits.

This data is uploaded to the machine’s control system and used to guide each pass of the dozer.

As work progresses, survey drones capture surface updates using LiDAR or photogrammetry at regular intervals and machine-mounted LiDAR, or GNSS-based sensors collect as-built data in near-real-time. This allows engineers or onboard systems to compare actual versus planned surfaces, update the digital terrain model, and reissue guidance files as necessary as shown below in Figure 1.

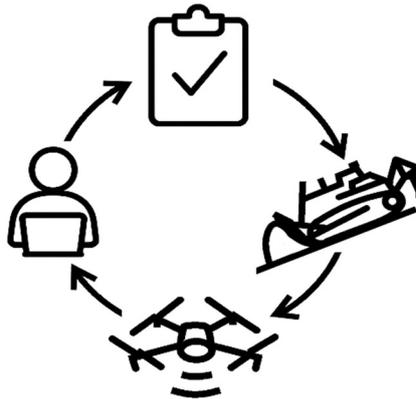


Figure 1 Illustration of the design update loop

This iterative design–construction cycle is essential in environments where material type, density and moisture content changes unexpectedly. Without such a system, autonomous dozers would either overwork areas or fail to meet final landform requirements leading to increased construction costs.

When properly implemented, this closed-loop system supports:

- reduced rework and unnecessary fuel use
- real-time identification of design constraints not met in the field
- continuous alignment with rehabilitation goals, even as conditions change.

The eventual deployment of fully autonomous systems that can respond intelligently without human intervention.

The challenge lies in integrating these systems in a way that is robust, scalable, and compatible with the realities of mine closure, especially in variable terrain and under regulatory scrutiny.

6 Case study: productivity gains from semi-autonomous tractor system dozer operations in Queensland, Australia

A comparative analysis was conducted on two bulk earthworks rehabilitation zones at a large open cut mine in Queensland, Australia. The objective was to assess the performance difference between manual dozer operations and semi-autonomous operations using Caterpillar’s SATS based on similar push distances and terrain grades. Productivity was measured in BCM/hr (bank cubic metres for in situ material not yet disturbed) or LCM/hr (loose cubic metres for material previously moved), benchmarked against expected output for each task type that accounted for the average push distance and grade.

The same model dozers (Caterpillar D11T with XU blade machines and identical technology package) in both trials were used in manual or semi-autonomous modes for the respective trial periods. Due to the nature of the system, not all tasks can be completed autonomously so a month was judged as applicable to the semi-autonomous trial if at least 50% of the total hours were in autonomous operation.

Data was gathered from logged machine hours, monthly survey surfaces captured using a drone, and daily as-built surface data (generated from GPS logging on the dozers).

6.1 Area 1: truck dumped spoil reshape of a ramp void

Dozers were used to reshape an old ramp void pushing truck dumps from either side into the void to reshape to a valley with 10% maximum grade. Material was easy to dig with only four hours of total ripping across the total project. Some water in the void was removed from survey surfaces using previous surface data. The volumes moved and productivity improvement are shown below in Table 1.

Table 1 Area 1 dozing results

	Manual operation	Semi-autonomous operation
Duration	2 months	8 months
Material moved	449,129 BCM	1,672,470 BCM
Autonomy utilisation	N/A	50% of SMU hours
Productivity improvement	Baseline	14% higher per hour
Push distance	90–100 m (average)	90–100 m (average)

6.2 Area 2: dragline spoil reshape

Longer pushing scenario where dozers were used to push dragline spoil down and over a reject dump to form a domed 3% grade landform. Material was easy to dig with no ripping required. The volumes moved and productivity improvement are shown below in Table 2.

Table 2 Area 2 dozing results

	Manual operation	Semi-autonomous operation
Duration	1 month	1 month
Material moved	49,500 LCM	77,000 LCM
Autonomy utilisation	N/A	65% of SMU hours
Productivity improvement	Baseline	23% higher per hour
Push distance	200–220 m (average)	200–220 m (average)

6.3 Observations

The following observations were made by the design team during the testing phase based on data supplied by the site and interactions with the site project manager, supervisors and operators:

- SATS operations delivered notable productivity improvements in both short and long push scenarios.
- Gains were most significant in longer pushes, where precision and consistency from semi-autonomy reduced fatigue-related inefficiencies.
- Design input required greater precision – smooth transitions, grade continuity, and staged data files were necessary.
- Update request from the site team occurred more frequently with regular contact between supervisors and the design team.
- Frequent design updates were requested by operators, necessitating strong collaboration between site and engineering teams.
- File size limitations required segmentation of larger projects into manageable zones.
- While engineering overhead increased, overall cost efficiency and performance improved.

These results suggest that with proper integration of guidance data and operator oversight, semi-autonomous systems can outperform traditional methods, providing a clear case for future investment but that greater input from engineering support is required

The uptake of advanced dozer technologies, particularly those used for reshaping and rehabilitation, has already begun to deliver measurable benefits. Sites are now achieving economically viable push distances exceeding 400 m, a significant improvement over traditional limits. These gains are largely attributable to better guidance systems, more efficient material routing, and reduced operator fatigue through semi-autonomous control.

In addition to productivity improvements, safety outcomes have also advanced. Autonomous and semi-autonomous dozers will be increasingly used in high-risk zones such as steep slopes, areas near pit water, and other hazardous locations where traditional manned operations present unacceptable safety risks. By removing operators from the cab, these machines help address long-standing exposure concerns while maintaining progress on essential closure works.

Although cost savings have typically been presented as just down to labour force reduction, in our experience the labour force generally stays a similar size due to the limited range of functions that can be performed autonomously and the additional technology support required. Therefore the cost reduction needs to come in the form of increased utilisation and productivity to cover the additional cost of implementing new technologies including but not limited to initial capital outlay and increased operational costs in technology support.

These results highlight that even without full autonomy, incremental adoption of guidance and remote-control systems is already transforming dozer-based rehabilitation by lowering costs, increasing reach, and reducing exposure to risk.

7 Impediments to adoption of autonomous dozing in closure operations

Mine closure activities represent a fundamental shift in priorities from resource extraction to the execution of final landforms and environmental rehabilitation. As this transition occurs, there is growing interest in applying semi-autonomous and fully autonomous dozing systems to increase efficiency and reduce operating costs. However, several operational impediments remain that must be addressed to support broader adoption.

One of the key challenges is the logistical planning required to keep autonomous dozer fleets fully engaged. Unlike haulage systems, which are typically the centrepiece of mine productivity planning, bulldozers often operate in support roles and are more reactive to other equipment cycles. On active sites, the planning priority is usually focused on keeping truck and shovel fleets at full utilisation, with dozer tasks being scheduled around their requirements.

This results in inconsistent workloads for dozers operating in semi-autonomous modes. When there is insufficient material available for productive autonomous operation, machines are often reassigned to manual operation for other tasks such as:

- assisting dragline operations
- supporting excavator floors
- maintaining haul truck dumps
- clearing roads or pushing coal.

In these cases, the mine continues to incur the cost of the autonomy technology, while also requiring full manual staffing, thereby reducing the cost-benefit ratio.

Traditionally, bulldozers have been regarded as multi-role machines, valued for their flexibility across production support and auxiliary tasks. However, in the context of mine closure – where cost efficiency, scheduling, and repeatable landform construction are paramount – this flexibility becomes a barrier to the systematic planning required for autonomy.

As mine sites shift toward closure-focused operations, and as bulk earthworks become the dominant use case for dozers, the economic drivers for investing in advanced dozing technologies may strengthen. This shift could catalyse the next wave of innovation in dozer automation; if equipment planning, material scheduling, and guidance systems evolve to support autonomy as a primary mode, not a secondary one.

Another major roadblock to the large-scale adoption of autonomous dozing in rehabilitation is the inflexibility in design. Typically, reshaping designs are created before construction and only updated as problems arise, and these updates can take weeks to create and approve for use. In this time, the machines often continue constructing the current design which can lead to rework when the revision is issued. It is important to have a mechanism to update the design regularly throughout the project and ensure that this process can be completed quickly or have an alternate work area to ensure dozers can continue uninterrupted.

8 Strategic outlook: the road to fully autonomous rehabilitation

As the mining industry moves into a new phase of lifecycle management, the strategic emphasis is shifting from maximising resource extraction to executing cost-effective, regulatory-compliant mine closure. Within this context, the integration of automation into mine rehabilitation offers an untapped opportunity to improve efficiency, reduce labour dependency, and increase the consistency of landform outcomes.

The successful deployment of autonomous haul trucks has shown what is possible when equipment is tightly integrated into mine planning systems and supported by repeatable, data-driven workflows. Translating these lessons to rehabilitation requires a shift in mindset: bulldozers must no longer be treated as general-purpose machines but as dedicated landform construction tools with high-precision guidance requirements and digitally linked work instructions.

In the coming years, three parallel developments will determine the pace and success of autonomous dozer adoption in closure works:

- Design integration: rehabilitation designs will need to evolve from static CAD outputs into dynamic, machine-readable models that incorporate slope constraints, material properties, and directional movement data.
- Operational planning: mine closure projects must begin to treat dozers as primary assets requiring structured task scheduling and material delivery plans similar to how production fleets are managed.
- Technology evolution: manufacturers and technology providers must deliver systems capable of full autonomy in unstructured environments, integrating real-time sensing, vector guidance, and adaptive feedback loops.

The opportunity lies not just in reducing costs, but in reshaping the way we approach final landforms, more predictable, more environmentally aligned, and more economically sustainable

9 Conclusion

The transition from human-operated to autonomous systems is well advanced in production, but mine rehabilitation has yet to catch up. As closure becomes a more prominent phase of the mining lifecycle, there's an urgent need to rethink how bulk earthworks are planned, executed, and guided.

This paper has shown how current semi-autonomous solutions, like Caterpillar's SATS, can deliver real gains in productivity and safety during rehabilitation. We have also outlined the design and data infrastructure required to support further automation, and the challenges that must be addressed to scale adoption.

To close mines better, faster, and more affordably, the mining industry must embrace:

- smarter, vector-based design workflows
- continuous design-to-machine feedback systems
- structured, autonomy-ready planning frameworks.

Autonomous rehabilitation is not just a technological shift; it's a strategic opportunity to reframe the way we approach mine closure and deliver long-term environmental and economic value.

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