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1. FOREWORD

The Global Mining Guidelines Group (GMG) is a network of representatives from mining companies, original equipment manufacturers (OEMs), original technology manufacturers (OTMs), research organizations, and consultants around the world, creating multi-stakeholder working groups to systematically remove the impediments to building the safe, sustainable, and innovative mines of the future. To achieve this goal, GMG working groups establish focused projects to develop guidelines, such as this one, for the international mining industry. Draft documents are checked and approved by working group members, prior to approval by the GMG Governing Council.

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2. ABBREVIATIONS

AI	Artificial Intelligence
ALARP	As Low as Reasonably Practicable
API	Application Programming Interface
CHAZOP	Control Hazard and Operability Study
FIFO	Fly-in Fly-out
FMEA	Failure Modes and Effects Analysis
HAZOP	Hazard and Operability Study
IP	Internet Protocol
ISO	International Organization for Standardization
IT	Information Technology
KPI	Key Performance Indicator
LOPA	Layers of Protection Analysis
OEE	Overall Equipment Effectiveness
OEM	Original Equipment Manufacturer
OMF	Open Mining Format
OT	Operational Technology
OTM	Original Technology Manufacturer
SWOT	Strengths, Weaknesses, Opportunities, and Threats
TCP	Transmission Control Protocol

3. KEYWORDS

Automatic, Autonomous, Autonomous equipment, Autonomous mining, Autonomous systems, Change management, Industry 4.0, Technological innovation

4. INTRODUCTION AND BACKGROUND

The mining industry is increasingly embracing automation as a safety and productivity enabler and as a critical factor in making future mining methods sustainable. Successfully implementing autonomous systems adds clear value: it can improve safety, increase production efficiency, and lower maintenance costs. Implementing autonomous systems also presents new challenges such as security and safety risks and workforce and workflow changes.

Whereas there are existing safety standards, such as the International Organization of Standardization (ISO) standard: Earth-moving machinery and mining—Autonomous and semi-autonomous machine system safety (2017; subsequent references are to standard number ISO 17757:2017 (International Organization for Standardization, 2017a) and the Western Australia Code of Practice for Safe Autonomous Mining (Government of Western Australia Department of Mines and Petroleum, Resources Safety, 2015; some sections in this guideline are adapted, with permission, from this source), mining stakeholders have identified a need for a global guideline that covers autonomous mining implementation more broadly. This guideline not only assists those implementing autonomous systems with maximizing the value of autonomy but also provides a framework for mitigating risks and managing change.

This implementation guideline provides mining companies, OEMs, OTMs, third-party solution providers, system integrators, regulators, and other stakeholders with the tools necessary to move forward with autonomous mining projects. The guideline serves as a first step, assisting companies implementing autonomous mining projects ranging from single autonomous vehicles and hybrid fleets to highly autonomous fleets.

This guideline:

- Provides a high-level checklist and playbook for implementation
- Outlines the risks and benefits of autonomous mining
- Offers a global and unified understanding to influence how key stakeholders approach autonomous mining
- Enables future autonomous mining innovation with the aid of common practices
- Communicates that implementation can be facilitated through cooperation between involved parties, including OEMs, OTMs, system integrators, and miners

As autonomous technologies are rapidly changing, this guideline will be reviewed and updated as needed.

4.1 Contextual Background

Automation is part of a broader industrial movement, often referred to as the fourth industrial revolution or Industry 4.0, which also includes robotics, artificial intelligence (AI), and the Internet of Things. This movement is marked by technology integration and interconnection, which can improve efficiency and productivity. To achieve these kinds of benefits, new technologies like autonomous systems require a holistic approach.

GMG's working groups have several projects underway tackling this broad movement toward greater connectivity. These projects complement this guideline, and relevant references will be added to the recommended reading list (Section 14) as they become available. They include ongoing and upcoming projects on:

- Interoperability, which is a necessity for implementing autonomous systems. A high-level definitions and roadmap guideline (GMG, 2019b) is in preparation.
- Open data and data exchange, which is needed to enable autonomous systems. The Data Access and Usage Working Group is addressing this topic. The first version of the Mobile Equipment Open Data Consensus Guideline is published (GMG, 2016), and the first version of the Open Mining Format (OMF), an open standard for geometric data transfer, was launched in 2017. Both projects are currently being updated.
- Short Interval Control, which is a process enhanced by automation. An implementation guideline is in its final stages (GMG, 2019a).
- Underground mine communications infrastructure, which is necessary for implementing autonomous systems underground. A guideline suite is being developed, and the first two parts have been published (GMG, 2017a, 2017b). The third is in its final stages (GMG, 2019c).
- AI, which can enhance many autonomous system capabilities. An educational project, Foundations for AI in Mining, is underway.
- Cybersecurity, which is a critical concern with integrated digital systems, will be a key topic for GMG in 2019.

5. SCOPE

This guideline communicates and educates using current industry practices and common terms of reference (defined in Section 6) and provides guidance on justifying, planning, developing, testing, implementing, and executing autonomous systems. It offers high-level guidance which recognizes that different levels of autonomous system maturity exist across mining operations (Section 6.2) and that requirements are varied depending on the type of operation.

This guideline covers the application of autonomous systems in mining and quarry operations and large-scale construction projects, including both new mine (greenfield) and existing mining (brownfield) operations and both surface and underground operations. These operations range from those dealing with *in situ* material, mining activities that contribute to material extraction (drilling, blasting, loading, haulage, dumping), to those from feed to processing plant (handling prepared material that is ready to process). Though this guideline is specific to mobile equipment operation, many of the guiding principles for fixed plant automation (which is mature compared to mining equipment automation) are the same.

Stakeholders in this process could include, but are not limited to:

- Management
- Information technology (IT)/Operational technology (OT)
- Operations and Maintenance
- Engineering
- OEMs
- OTMs
- Support services (e.g., safety and emergency response, human resources, risk management)
- Internal and external subject matter experts
- Legal representatives
- Regulators
- Financial representatives
- Corporate affairs
- Unions
- Communities
- Educational facilities (universities, training academies)
- Governments
- Suppliers
- Environmental approvals and compliance departments and agencies

After defining common terms of reference, this guideline is structured around the key areas of consideration for those implementing autonomous systems. These topics are presented in Sections 7–12: change management, developing a business case, health and safety and risk management, regulatory engagement, community and social impact, and operational readiness and deployment. Though arranged in broadly chronological order, many of these considerations must happen simultaneously and inform each other. The appendices provide additional contextual information, checklists, considerations, and examples.

5.1 Principles of Scope

This guideline does not replace safety requirements, regulations or duty of care. It acknowledges that regulatory bodies and standards already exist that influence the processes at various stages of the mine cycle. This guideline should be taken in the context of integration into the overall mining cycle value chain.

6. COMMON TERMS OF REFERENCE

This section outlines key terminology and a maturity model for autonomous mining and defines broad implementation approaches.

6.1 Terminology and Definitions

Because this guideline deals with concepts and operational processes where the specific terms often vary depending on the mine and region, this list identifies terms the guideline applies to describe these concepts and disambiguates terms that are often used interchangeably. Definitions are informed by standard language in ISO 17757:2017 (International Organization for Standardization, 2017a) and the Western Australia Code of Practice for Safe Autonomous Mining (Government of Western Australia Department of Mines and Petroleum, Resources Safety, 2015).

Automatic: A process or part of a process when a machine follows well-defined rules.

Automation: The technique, method, or system of operating and controlling a process or machine by automatic means with minimal human intervention.

Autonomous: A process or machine that is intended to accomplish task(s) within a set of defined operations without human intervention or direct control.

Autonomous area: The area in which autonomous equipment operates.

Autonomous operator: The person who operates an autonomous process or machine and takes control when necessary.

Autonomous supervisor: The person who supervises one or several autonomous processes or machines at high levels of equipment maturity and intervenes when necessary. This role overlaps with that of the autonomous operator.

Autonomous system: A system that can perform desired tasks in unstructured environments without continuous human guidance.

Availability: The amount of time in a defined period during which an asset is available to provide the needed function.

Component: A part of a larger whole. In this guideline, component refers to components of individual machines and components of integrated systems.

Control room: A facility from which dispersed operations, systems, and equipment can be monitored and controlled; often also called an operations centre.

Implementation plan: The high-level plan developed for implementing autonomous systems in mines.

Manned operation: An operation where a human is at the location and operating the equipment.

Manual operation: An operation where a human is in control of the equipment. This can be either manned or remote control.

Mobile autonomous mining: Mobile equipment operated using an autonomous system.

Operational readiness: The capability to operate a new system, technology, or piece of equipment. This involves having people, processes, controls, and infrastructure in place.

Organizational readiness: Having a business structure that is ready for a desired change.

Redundancy: Duplication of components or functions to create a backup or fail-safe mode in which to operate after a disruption.

Reliability: A measure of the dependability of a system to perform at a defined quality.

Remote controlled: A type of operation where the functionality and operator interface are the same or similar on the machine but the controller is separate from the machine and is under human supervision while the machine is operated in line-of-sight or tele-remote mode.

Safe state: Operating or shutdown equipment condition whereby a hazardous event is unlikely if autonomous activity continues.

Semi-autonomous: A process or machine that is intended to accomplish a portion of assigned task(s) within a set of defined operations without human intervention or direct control.

Situation awareness: The ability to perceive environmental elements and comprehend their meaning and, in some cases, project the future status.

6.2 Maturity Model

This subsection outlines a maturity model for autonomous mining (Figure 1). The model assigns levels of autonomy that can be used to describe specific pieces or types of equipment, as well as stages of maturity that reflect the overall operation's level of autonomy.

The levels assigned to mining equipment are based on those outlined in the SAE International (2018) taxonomy of driving automation terms and adapted to apply to mining automation using standard terminology from ISO 17757:2017 (International Organization for Standardization, 2017a). The levels are defined as follows:

- Level 0: No automation: Equipment is operated entirely manually. Operator completes all tasks.
- Level 1: Operator assistance: The system has some function-specific automated features. The operator maintains control throughout the entire task.
- Level 2: Semi-autonomous: The system performs a portion of its tasks autonomously within a set of

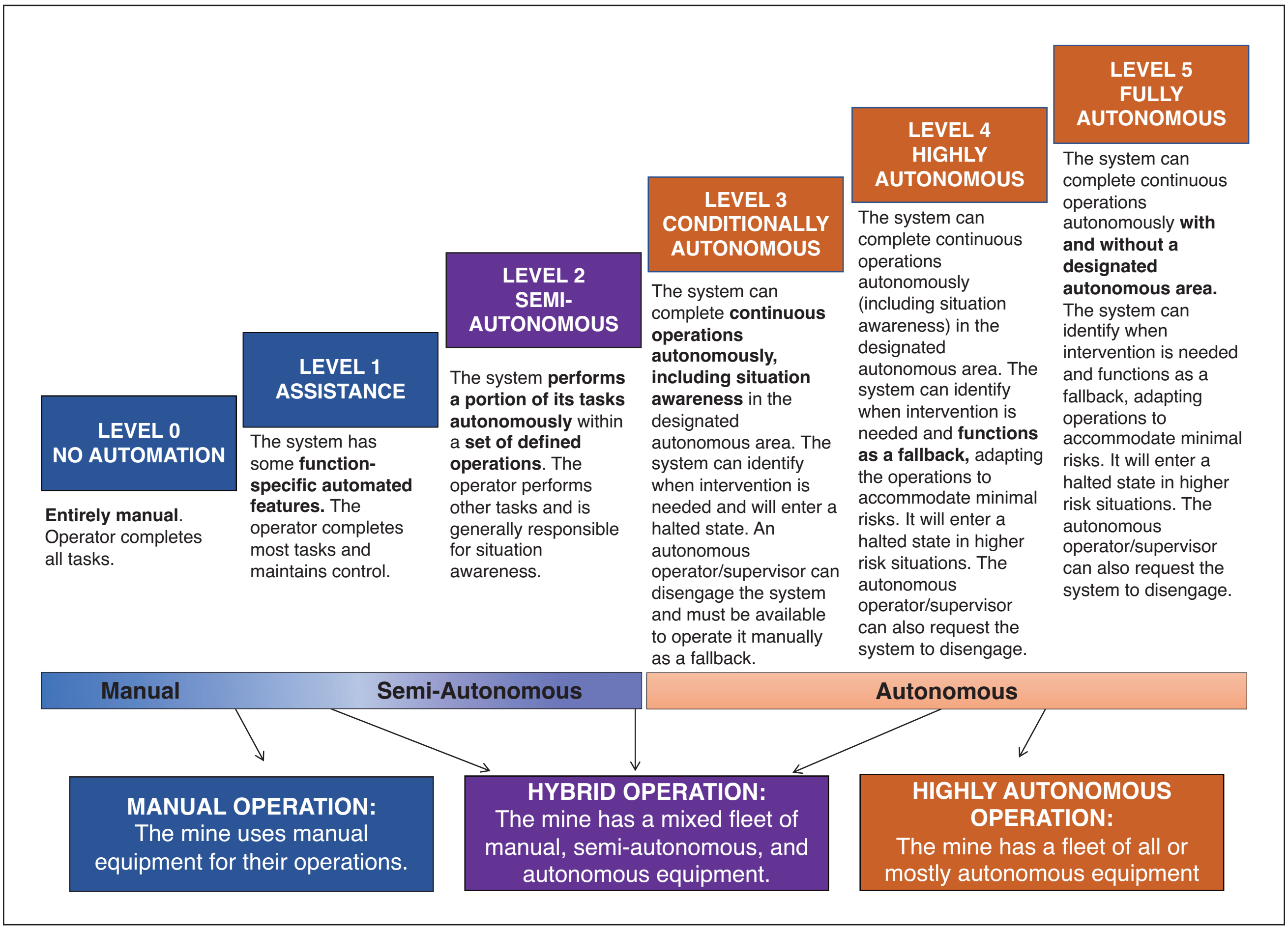

Figure 1. Mining Automation Maturity Model (Figure Design, GMG)

defined operations without human intervention or direct control. The operator performs other tasks. Remote control is often in place at this level, though it is not required.

- Level 3: Conditionally autonomous: The system can complete sustained operations autonomously in a designated autonomous area. It has situation awareness capabilities and enters a halted state when intervention is needed. An autonomous operator/supervisor can disengage the system at any time and must be available to operate it manually if necessary.
- Level 4: Highly autonomous: The system can complete sustained operations autonomously in a designated autonomous area and has situation awareness capabilities. The system can intervene in minimal risk situations. In higher risk situations, it enters a halted state. The autonomous operator/supervisor is able to request the system to disengage.
- Level 5: Fully autonomous: The system can complete sustained operations autonomously both with and without a designated autonomous area and has situation awareness capabilities. The system can intervene in minimal risk situations. In higher risk situations, it will enter a halted state. The autonomous operator/supervisor can request the system to disengage.

Levels 0–1 are manual because there is still continuous human guidance. Level 2 is semi-autonomous, and the level of human guidance varies. Levels 3–5 are autonomous because the system completes continuous operations.

A given mine's autonomous operational maturity is defined as follows:

- Manual operation: The mine uses manual equipment for their operations (levels 0–1).
- Hybrid operation: The mine has a mixed fleet of manual, semi-autonomous, and autonomous equipment.
- Highly autonomous operation: The mine has a fleet of all or mostly autonomous equipment (levels 3–5).

6.3 Implementation Approaches

There are many ways mines can implement autonomous systems. Possible implementation approaches for mines replacing old systems are:

- Slow implementation: A lower risk but higher cost approach where implementation is extended over a long time period with multiple checkpoints (e.g., of concept, trials, multiple releases). This approach allows the mine to incorporate research and development efforts.
- Phased implementation: A medium risk and medium cost approach where implementation is completed in paced stages with two or three checkpoints. This approach often involves implementing a mix of mature and agile solutions.
- Fast implementation: A higher risk but lower cost approach where the new system completely replaces the old one. This approach often involves implementing mature commercial solutions.

There is also variation within these approaches based on each mine's situation.

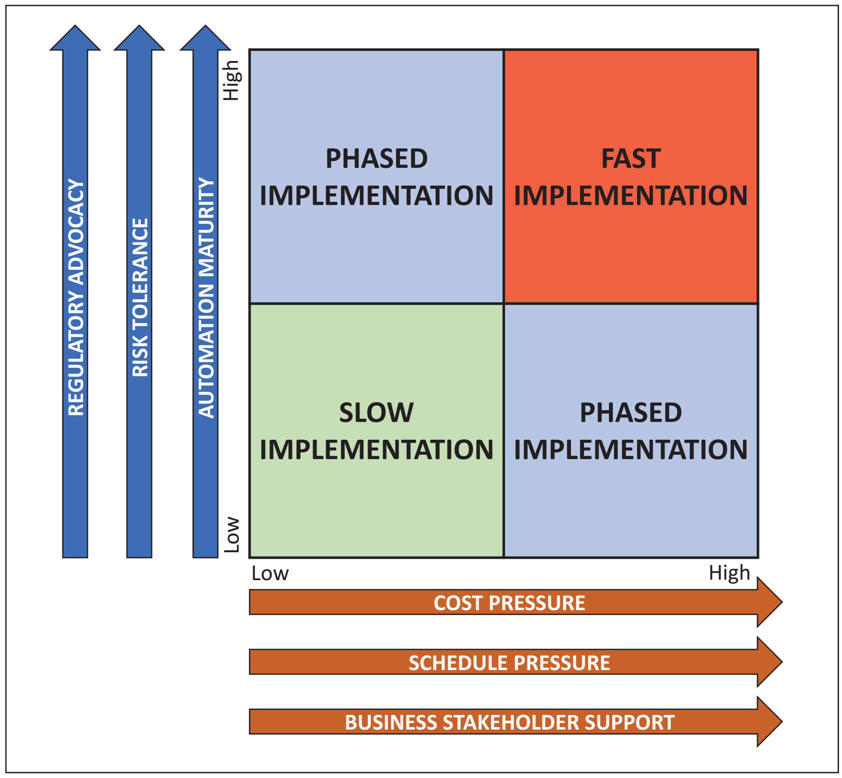

Figure 2. Factors Influencing the Choice of Implementation Approach (Figure Design, GMG Contributor)

The choice of approach depends on several factors. Figure 2 represents how low or high regulatory advocacy, risk tolerance, autonomous operational maturity, cost pressure, schedule pressure, and business stakeholder support can be used to determine the appropriate approach.

7. CHANGE MANAGEMENT

Implementing autonomous systems is a holistic organizational and cultural change; change management must be a primary consideration throughout all stages of the process. Ultimately, change management aims to achieve a situation where stakeholders have the appropriate level of trust that the change is useful, support the implementation process, and understand the benefits and risks of the new system. Change management processes vary depending on whether it is a greenfield or brownfield site, the type of activity, the planned level of autonomous maturity, the components to be automated, and the implementation approach. This section covers the topic broadly and provides some suggestions for how to approach change management based on industry experience.

7.1 Change Management Plan

For the implementation project to realize the business benefits associated with automation, a clear and transparent cultural change management plan must be executed concurrently. It should also be reviewed regularly throughout implementation to incorporate necessary adjustments based on unexpected situations.

Key recommendations for developing a change management plan for implementing autonomous systems include:

- Establish visible management support and commitment, such as executive sponsorship. Such support adds credibility to the entire process.
- Engage champions at all organizational levels from the outset; this can encourage other employees to support the change. Champions should be selected carefully: they should not only include early adopters who tend to be open to new technology, but also individuals who might not typically champion new technologies or processes.
- Have a single on-site person or team responsible for analyzing data, ideas, and interpretations brought forward from multiple champions at different organizational levels; this person would then recommend actions.
- Have a single on-site person or team to contact with questions and concerns about the incoming system, someone who can dispel rumours or misgivings and

disseminate facts. This activity is also valuable for user adoption/compliance.
- Provide ways for those affected to make positive contributions. This effort helps to create a culture that is open to change, thereby reducing the chances of resistance or minimal enthusiasm.

A well-developed communication plan is also vital to implementation. Successful change management communication can be accomplished by:

- Crafting a clear and consistent message covering what the changes are, why they are important for the business, when they will happen, who they will affect, and how they will be implemented.
- Communicating the message to stakeholders (see list in Section 5) at the appropriate time, explaining why the change is important for them, and managing their expectations.

Communication should occur early and often, and it should address questions and concerns that are important to the front-line staff and supervisors. Connecting with what is important involves discerning how the technology benefits front-line staff and supervisors by making their jobs safer and easier or helping them to achieve desirable results (see also Section 8). Communication is most effective across a variety of channels (e.g., email, engagement sessions, social media, posters) when messages are targeted based on who (which stakeholders) and how (i.e., one-way, two way, interactive) they engage.

Established methodologies for change management can help to guide the approach. One example, Kotter's (2012) 8-Step Model, is outlined in Appendix A.

7.1.1 Critical Success Factors

The change management plan should identify critical success factors—the areas of the project that are essential for success. These should be measured and monitored throughout the process (Table 1).

7.2 Change Management Progression

Change management considerations should evolve as the project progresses through project preparation, implementation, and early operation (Figure 3). Three major aspects of change need to be considered at all stages:

1. Workforce management
2. Stakeholder engagement
3. Process management

Throughout the entire process, ongoing operational readiness assessments and planning, risk management, project controls, and management reporting also need to be conducted.

Figure 3 outlines essential change management considerations for implementing autonomous mining systems at different stages of the project. It represents a mine that is moving from a current ("as-is") state as a manual operation to a future ("to-be") state as a highly autonomous operation, following either a slow implementation or staged process. Many of these considerations are discussed in more detail in other sections of this guideline.

8. BUSINESS CASE

This section assists those planning or preparing a business case for autonomous mining. Before implementing autonomous systems, there needs to be a well-defined business case that addresses potential issues and opportunities that can affect desired outcomes. Because every company has different requirements and implementation processes vary, it is not possible to provide explicit instructions. Instead, this section provides considerations for the business case to help readers produce accurate and complete business cases that are applicable to their situations.

Table 1. Critical Success Factors for Change Management

Critical success factor	How to measure
Level of authority	Level of support/sponsorship Approvals
Inclusiveness	Stakeholder analysis
Quantified risk	Risk analysis
Realization of value	Business case value drivers, key performance indicators (KPIs)
Change management competency	Measure process improvement Influencers identified and engaged Presence of informal leaders/change champions
Safety	Safety risk identification Hazard controls

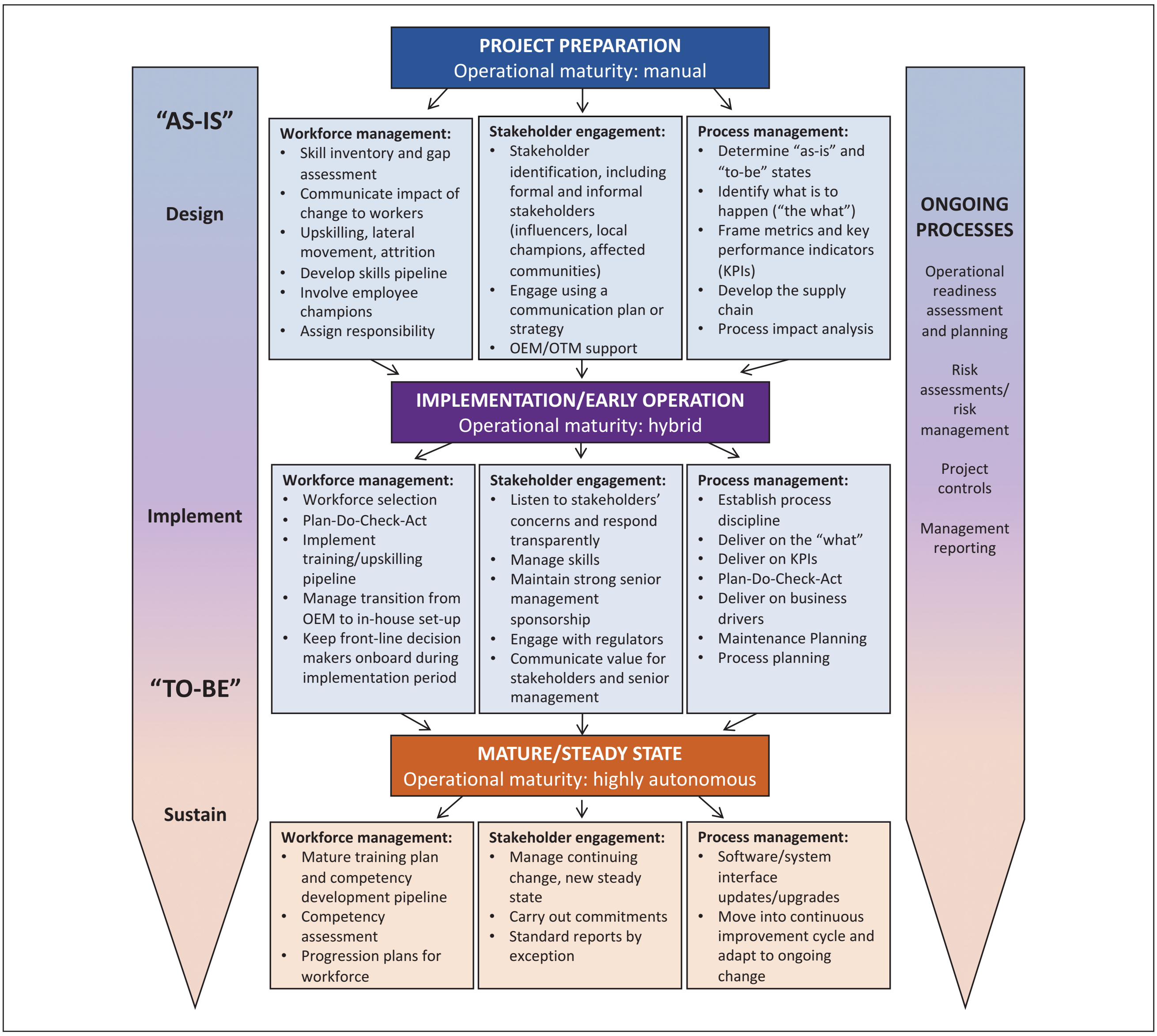

Figure 3. Change Management Progression from Preparation to Mature/Steady State (Figure Design, GMG)

Comparison between the "as-is" state (reviewing current constraints and issues), and potential "to-be" state (the new system's capabilities and enablers) is the basis of the business case. The business case addresses the following:

- Why automation is desirable
- What level of maturity to implement, including:
  - What components/processes/tasks to automate (for hybrid operations) and which ones to automate first (in a slow or staged implementation process)
  - What components/processes/tasks will be more highly automated (e.g., equipment maturity levels 4 and 5 versus level 3)
- How to approach implementation (slow implementation, phased implementation, or fast implementation, see Section 6.3)
- How long the transition will take (a realistic time frame between initial implementation and steady state operations)

The business case also:

- Defines the financial, operational, and safety risks associated with automation
- Defines positive and negative externalities (i.e., the costs or benefits to to third parties)
- Analyzes the potential solution's strengths, weaknesses, opportunities, and threats (SWOT analysis)
- Defines KPIs to evaluate and measure success

8.1 Safety Considerations for the Business Case

One benefit frequently associated with autonomous mining systems is increased safety; however, these systems also present new safety risks. While all business cases must consider all types of risks associated with the project, it is especially important to consider both the safety benefits and risks of automation. The business case should address the following questions about safety:

- What are the expected safety and organizational benefits?
- What are the hazards associated with the transition to the new technology?
- If there is an existing operation, what hazards can emerge that need to be considered and managed during integration?
- What is a realistic lead time for full implementation, given the need for verification and validation trials as part of the risk management process?

Companies should invest sufficient time and resources to ensure autonomous operations can start up safely and meet production expectations. Matters to be considered include:

- Organizational and operational readiness
- Project management
- Site-specific risks

See Section 9 for more specifics about health and safety and risk management for autonomous systems.

8.2 Holistic Change Considerations for the Business Case

Introducing autonomous systems is a holistic change. The business case must communicate why such a shift is necessary and valuable while also addressing the potential costs and risks involved (see Appendix B for lists of potential benefits, value drivers, and costs). The business case should consider the "as-is" and "to-be" states specific to people, processes, and technology.

8.2.1 People

Introducing automation affects the workforce, and the following potential changes need to be identified and managed carefully.

- The size and shape of the workforce: Changing operational processes and requirements will influence the size and shape of the workforce (e.g., there might be more options for remote work and fewer people on-site).
- Roles, skill requirements, and competencies: New skills will be part of new organizational structures and some existing skills might no longer be applicable.

The costs (e.g., training) and benefits (e.g., improved safety) of these changes need to be considered as part of the business case (see Appendix B). Ultimately, the "to-be" state for people involves cultural change where the new way of doing things becomes habitual and where people are open to ongoing change. Section 11 covers many of these changes, how to assess them, and how to engage the community.

The business case for people will differ between greenfield and brownfield mining operations. New mining operations can build their management and workforce structure to support autonomous mining from the beginning. Existing mines have to consider the transition costs (e.g., retraining and upskilling) to change the organizational structure.

8.2.2 Processes

Automation affects many mining processes, such as traffic management plans, safety management plans, safe work procedures, work instructions, interfacing between autonomous areas and maintenance, and shift management. The increased potential for remote services and work also changes processes and introduces new organizational processes and challenges (e.g., managing time zone differences and offering language support). These changes need to be identified and addressed promptly, and the mine layout, mine design, mine plans, and schedules need to be tailored to accommodate autonomous equipment (see Section 12). The business case should address possible benefits (e.g., reduced process variability) and costs (e.g., time and resources required for implementing these changes) (see Appendix B).

8.2.3 Technology

Implementing autonomous equipment requires companies to apply supporting technology, such as sophisticated and robust wireless communications networks and control rooms. These need to be identified and be part of the operational readiness planning and deployment process (Section 12). The business case should consider how technology continuously evolves; this involves considering potential new technologies and their impact on the scope and business case. Those implementing autonomous systems also need to understand the cost to study, select, and implement support technology, understanding the cost and risk of poor interoperability associated with closed systems and closed standards for technology. See also the interoperability definitions and roadmap guideline (GMG, 2019b).

8.3 Value Drivers

The business case should communicate the project's value drivers. For technology implementation projects, value drivers refer to the increased value that the new technology brings. Some value drivers are easily measured (e.g., reduced downtime) or refer to a specific cost reduction (e.g., lower insurance rates), while others are more difficult to measure (e.g., improved safety). Value drivers vary depending on many factors, so each potential value driver must be carefully considered in the appropriate context. Value drivers can help with financial and sensitivity analysis, determining strategic fit, and developing communications strategies.

Key drivers for implementing autonomous systems include (see Appendix B for a more extensive list):

- Improved safety from separating humans from hazardous situations
- Reduced personnel support costs from the possibility of remote operations (e.g., accommodation and travel for fly-in fly-out [FIFO] operations)
- Improved productivity from reduced variability and increased efficiency in processes
- Improved overall equipment effectiveness (OEE) from optimized processes and increased situation awareness
- Improved mining strategies (e.g., autonomous systems can offer smaller truck/digger sizes, which can reduce maintenance and underground ventilation costs)

8.4 Costs

The business case also needs to consider the costs associated with autonomous system implementation. These costs include, but are not limited to:

- New technology and equipment
- Supporting infrastructure
- Training
- Ongoing updates and technical support

See also Appendix B.

8.5 Strategic Fit

It is necessary to ask whether autonomy is an explicit corporate strategic goal: the lack of a strategic fit can derail the business case from the corporate standpoint. The organization's leaders need to understand the current state to assess whether or not the organizational change and the costs associated with adopting autonomous systems align with their goals and are strategically viable. There are situations where autonomous systems are not viable at all or where a highly automated operation is not viable, and a hybrid one would be preferable. Table 2 provides examples of situations where there may be a strong strategic fit and where the strategic fit may need more consideration. The operation's current scope and autonomous operational maturity and the organization's current capacity and capability are important factors. For example, automation can compound poor reliability and poor availability if it is not handled correctly.

Individual mines should make decisions concerning technologies and components based on the appropriateness to their specific operation. Autonomous technologies and components vary in maturity (Section 6.2) and applications. The strategic fit discerns which maturity level(s), implementation approach, and specific applications are most appropriate.

The business case also needs to consider the possibility that automation can unlock new business models. New models require new plans, such as lease versus buy or mining as a service—where a third party to the OEM and mining company offers automated mining as a service to the mining company by assembling a full system offering composed of elements that OEMs provide. Some understanding can be gleaned from other industries and generic packages on makes or models.

8.6 Communication with Stakeholders

Should the business case demonstrate positive value, promoting the business case is essential. It is necessary to understand the audiences and their values in order to

Table 2. Guidance for Assessing Strategic Fit for Automation

Strong strategic fit	Strategic fit may need more consideration
Long life and large scale	Short life, small, intermittent
Labour constraints, high turnover	Social licence requires employment
Highly efficient operation	Inefficient operation
New automation-ready equipment	Old equipment with short remaining mine life
Remote, challenging logistics	Low-quality planning
High altitude, difficult environment	Constraints in upstream and/or downstream processes
Greenfield projects	Immature project delivery capability
Highly variable commodities	Local community with high capability in existing technologies
Mature health and safety	
High change acceptance	

achieve acceptance by the mine site and gain strong operational ownership. Stakeholder participation is also essential. During the business case development process, identify and include key stakeholders at the mine to promote the changes rather than have higher level decisions handled by those not embedded in the mine culture. Develop the business case with participation and input from corporate and site levels. It is important to teach all stakeholders about the problems that they face, and how the solutions can enhance their overall efficiency and safety. See also Sections 5, 7.1, and 11.

8.7 Business Risks and Potential Problems

Consider the risk of the organization not being able to achieve the change. Ask: What is the delivery capacity of the organization? Be aware of the following potential problems:

- Delays to allow for "growing pains"
- Long-term OEM commitment
- Change in mine plan (e.g., caused by market issues)
- Legacy issues
- Obsolescence
- Difficulties related to change out

8.8 Other Considerations

- Assumptions: Identify realistic and specific scenarios that the mining company assumes will happen.
- Transparency with regulators: See Section 10.
- Timing: Determine the estimated timeframe for implementing autonomous systems and follow a proper stage gate evaluation process. Consider investment return times and the overall operation lifetime.
- Financial and economic analysis: Determine the appropriate balance between capital expenditures and operating expenses, consider the return on investment, and consider financial opportunities (e.g., tax deductions). Complete different types of financial analyses such as:
  - Internal rate of return analysis
  - Net present value analysis
  - Discounted cash flow analysis
- Environmental and social analysis: Analyze strengths and weaknesses of the business/trade environment internally and externally (e.g., SWOT analysis) and analyze social impact (see Section 11).
- Alternatives: Identify alternatives to implementing autonomous systems and alternative ways of implementing autonomous systems (e.g., if the business case is for highly autonomous operations, an alternative might be for hybrid operations).
- Organizational readiness: Consider changes in roles and responsibilities and in the organizational structure resulting from automation and how to approach them.

9. HEALTH AND SAFETY

This section provides guidance for developing health and safety management plans in an autonomous mining environment. Safety must be a standalone part of the implementation plan and included in other plans as necessary. Those planning to implement autonomous systems must address all safety requirements up front and establish a safety culture applicable to autonomous mining. This section describes safety requirements generally, but GMG has also identified the need to create a separate guideline on functional safety for autonomous mining equipment, which will be added to the recommended reading when available.

Safety requirements for autonomous systems are varied. Broadly, they can be considered in the following categories:

- Environmental health and safety (e.g., weather, heat, ventilation)
- Facilities (e.g., machinery, buildings, roads)
- People (e.g., workforce, site visitors)
- Processes
- Community
- Cybersecurity (this will require separate attention and will be covered in more depth the forthcoming functional safety guideline)

Because health and safety processes change over time, effective change management processes (Section 7) are necessary to ensure the processes, workforce, and stakeholders are ready to meet new health and safety requirements.

Effectively managing the health and safety risks associated with operating an autonomous mining system requires input from diverse operational groups, including:

- Researchers
- Design engineers
- Project managers
- Team leaders
- Control room operators
- Health and safety representatives
- Emergency response personnel
- Any other workers involved in the tasks

A safety committee should be established to identify risks and determine the training required.

Those implementing autonomous systems need to delineate how roles and responsibilities might change from the previous system. It is recommended to create a responsibility assignment matrix (such as "responsible, accountable, consulted, informed" or "responsible, accountable, supportive, consulted, informed"). These would specify the owner/contributor of the information for implementing the autonomous solution of choice and what that provider is expected to submit. This matrix would include, but not be limited to OEMs, operators, consultants, third-party technology providers, and regulators.

The system must comply with all regulations and safety standards, including local regulatory requirements (Section 10). The new system should also gain approval from authorities at all stages, ideally undergoing a peer-review process. Those planning for safety should compile a list of established standards with a classification of what they represent, their purposes, and applicability. Table 3 offers a preliminary list of relevant international standards. The full citations and links to these standards are presented in Section 14. The final list should include regional and geographic nuances (such as environmental variability or geopolitical risk) but where possible reference globally accepted documents (e.g., ISO).

The project must undergo a rigorous risk assessment and management process specific to health and safety; the following subsections outline this process. The process and terminology are based on those described in ISO 17757:2017 (International Organization for Standardization, 2017a).

Once the system is planned, verify:

- That it meets functional safety requirement
- That it is prepared for ongoing maintenance implications (test/validate/response)
- That there are emergency response plans in place

Appendix F describes some examples of incidents and lessons learned.

9.1 Risk Management

The risk management process involves identifying the system's functional safety requirements and identifying and planning to manage potential risks and hazards. It is recommended to create a risk evaluation matrix that covers incident management, human errors, and change management planning. Deployment scheduling, site preparation, communications, contingency, vendor partner selection, execution, support and handover, and business continuity should have separate plans. Plans will vary to accommodate different mine types and operational and equipment maturity.

Communication and consultation are necessary for effective risk management. Those with knowledge of the autonomous mining system design, engineering, commissioning, operation, and maintenance should be involved in assessing and minimizing associated risks during the operational life cycle.

9.1.1 Risk Identification

It is important to identify how using autonomous technology changes established safety systems and any

Table 3. Recommended International Standards Relevant to Health and Safety and Risk Management

Standard number	Title	Citation
IEC 60204-1:2016	Safety of machinery – Electrical equipment of machines—Part 1: General guidelines	International Electrotechnical Commission, 2016
IEC 61508-1:2010	Functional safety of electrical/electronic/programmable electronic safety-related systems—Part 1: General requirements	International Electrotechnical Commission, 2010
IEC TS 62443-1-1:2009	Industrial communication networks–Network and system security–Part 1-1: Terminology, concepts and models	International Electrotechnical Commission, 2009
ISO 13849-1:2015	Safety-related parts of control systems—Part 1: General principles for design	International Organization for Standardization, 2015a
ISO 13849-2:2012	Safety-related parts of control systems—Part 2: Validation	International Organization for Standardization, 2012
ISO 31000:2018	Risk management—Guidelines	International Organization for Standardization, 2018c
ISO 20474-1:2017	Earth-moving machinery – Safety—Part 1: General requirements	International Organization for Standardization, 2017b
ISO 19296:2018	Mining – Mobile machines working underground—Machine safety	International Organization for Standardization, 2018a
ISO 17757:2017	Earth-moving machinery and mining—Autonomous and semi-autonomous machine system safety	International Organization for Standardization, 2017a
ISO 73:2009	Risk management—Vocabulary	International Organization for Standardization, 2009
ISO 12100:2010	Safety of machinery – General principles for design—Risk assessment and risk reduction	International Organization for Standardization, 2010
ISO 45001:2018	Occupational health and safety management systems—Requirements with guidance for use	International Organization for Standardization, 2018b

risks and hazards associated with those changes (see Appendix C.1 for a list of hazard identification systems and processes). This process might involve identifying safety functionality and operational process limitations of the autonomous system. The following questions can help to identify autonomous mining health and safety risks.

1. What are the potential scenarios for autonomous mining incidents?
2. What are their potential consequences concerning safety and health?

9.1.2 Risk Analysis

At the risk analysis stage, mine sites should determine the nature of the hazard and the risk level, considering the likelihood of an incident, potential severity of injury or damage, and ability to identify an incident. Those assessing the risk must have the necessary information, training, knowledge, and experience of the:

- Operational environment (e.g., scale, complexity, physical environment of mining activities)
- Operational processes (e.g., maintenance systems, work practices, interaction, separation)
- Autonomous systems (e.g., functionality, functional safety requirements, safety features)
- Site continuity plan
- Corporate risk guidelines

9.1.3 Controls for Risk and Hazard Management

Once health and safety risks hazards have been identified and analyzed, it is essential to put appropriate controls in place to prevent and/or reduce their risk and minimize potential consequences (see Appendix F for specific examples). Start by asking: What controls are available, and how effective are they? This question is best answered by applying a hierarchy of controls (Figure 4). Types of controls are listed below from 1 (most effective) to 5 (least effective):

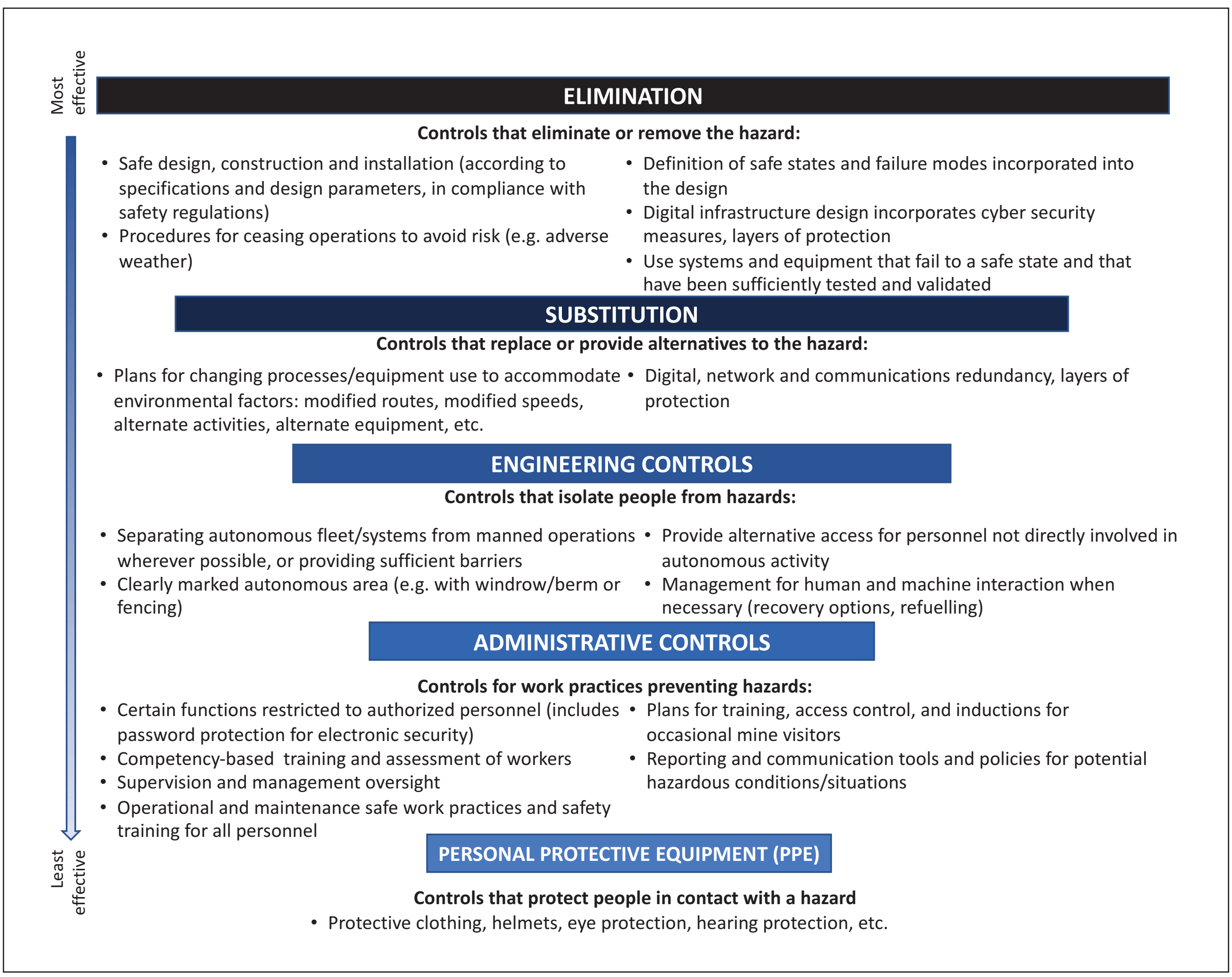

Figure 4. Hierarchy of Controls for Autonomous Mining Systems (Figure Design, GMG)

1. Elimination controls eliminate or remove the hazard (e.g., designing for safety).
2. Substitution controls provide alternatives to the hazard (e.g., alternative routes).
3. Engineering controls isolate people from hazards (e.g., separating autonomous and manned operations). Appendix C.2 lists controls at the first three levels that are specific to maintenance activities.
4. Administrative controls for work practices prevent hazards (e.g., providing sufficient safety training for personnel, see Appendix C.3).
5. Personal protective equipment reduces the consequences of a safety incident (e.g., protective clothing).

When determining how to implement various controls, mine sites must ensure they provide sufficient information for decision-making. Though the systems are autonomous, human decisions are still required to overcome exception states for autonomous systems at all maturity levels. The system should be designed such that alerts and alarms on the machines and in the control room are prioritized with humans in mind.

9.1.4 Monitoring and Review

A monitoring and review program should be implemented that includes control audits, verification, and validation to ensure controls are effectively maintained at the mine site. Responsibilities and accountabilities should be clearly defined and assigned as part of the mine site's validation process and may include independent auditing. The findings should be used to:

- Confirm that the recommendations from previous reviews have been actioned
- Confirm that appropriate responses have been made to any incidents or issues
- Verify compliance with specifications (e.g., inspection, monitoring, quality control)
- Recommend any necessary operational or system design modifications, which are documented and managed through a formal change management process

Mine sites should also consider that autonomous systems create a greater dependency on instrumentation to report equipment health and incidents.

9.1.5 Documentation

The risk assessment results need to be formally documented in the operation's risk register in compliance with regional and/or national regulations. Details should include:

- Locations of autonomous areas
- Size, mining methods, and complexity of operations
- Autonomous maturity
- Types of potential incidents
- Consequences and likelihood of each incident
- Controls used to mitigate each risk
- Monitoring and review outcomes and actions

Documenting this information forms the basis of the mine site's safety plan for autonomous mining systems and facilitates communication with other sites and operations.

9.2 Emergency Management Planning

Emergency management involves understanding the likelihood and potential consequences of an emergency event and being prepared to mitigate its effects, respond effectively, and recover afterwards. Effective emergency management identifies all foreseeable emergency scenarios and develops emergency response plans for each so that there is a comprehensive and coordinated response if they occur. These plans should also take into consideration that safe access and effective communication can be difficult to establish and maintain during an emergency. Emergency response planning for autonomous operations should be integrated with the overall emergency response planning for the mine where necessary.

The mine site must establish the following:

- An emergency response plan
- Accident investigation and root cause analysis procedures
- Recovery methods after an emergency

The autonomous safety system should include emergency response procedures to isolate all or part of the autonomous area safely and shut down the equipment. Tiered shutdown is preferable. For example, two-tier isolation circuits—where the first tier isolates all primary power (actuation systems) and the second isolation layer is for the controller/telemetry system—have been shown to be safer in underground situations because the telemetry can influence the emergency response.

All personnel should be familiar with the emergency response strategy and understand their responsibilities in an emergency before entering the mine site. Before entering an autonomous area, the emergency response team should understand how the system works and the controls that are required. A member of the autonomous mining team should brief emergency personnel and might be required to escort them to the location.

Emergency response plans should be regularly tested to ensure they are effective with both simulated tests and emergency response drills involving all on-site personnel. The drills can be used to evaluate how people respond, and debriefings should be conducted as soon as practicable after an emergency or drill to help identify potential improvements to the emergency response plan.

10. REGULATIONS

Autonomous mining methods often require regulatory changes. Establishing regulatory requirement changes must be done early in the process because existing regulations can have unintended consequences and are often inconsistent when it comes to autonomous systems (see Appendix F for case studies that exemplify some possible consequences). Implementing autonomous mining methods might require:

- Exemption from existing regulations
- Development of entirely new regulations
- Updating some existing regulations
- A combination of the above

Those implementing autonomous systems might encounter gaps in regulators' understanding when defining new and updated regulatory regimes and should be prepared to discuss how regulations might need to change. This discussion needs to happen early in the process because regulatory changes take time. Eventually, quality assurance and quality control checklists must be created to ensure compliance.

10.1 Adapting Regulations to Autonomous Mining

Existing regulations often need to be adapted to accommodate both technological and procedural changes, such as different equipment types (e.g., scoops versus haulage trucks) associated with autonomy. Levels of autonomy, such as those outlined in Section 6.2, could be developed around equipment types.

Though many current regulations were written without autonomous systems in mind, a person or team should be able to grasp the sense of an existing regulation by considering what it intends to accomplish and seeking to meet or exceed that expectation.

10.2 Engaging Regulators

Actively engaging with local and regional regulators is essential to successful autonomous system deployment; it is important to consider how to approach regulators. Consider when to begin this process of engagement, what material needs to be shared with regulators, and for which milestones follow-up discussions are needed. Initial steps are as follows:

1. Identify applicable regulators and regulations and understand legal liability related to operating autonomous systems
2. Conduct a gap analysis of standards, regulations, and norms for which compliance might be challenging that identifies what needs to change
3. Based on the gap analysis, determine the level and type of engagement with regulators (e.g., adjustments to existing requirements is generally simpler than developing entirely new regulations or addressing current regulations that are prohibitive and incompatible with autonomy)
4. Evaluate those stakeholders who need to be part of regulatory engagement
5. Consider the time it takes to get regulatory approvals

Organizations can do the following to facilitate engagement with regulators:

- Understand the regulator's autonomy knowledge and maturity
- Bring in a subject matter expert when meeting regulators who has knowledge of how the autonomous system works to help maintain credibility
- Understand the differences between autonomous systems at different maturity levels (such as those outlined in Section 6)
- Share project management plans outlining how the autonomous systems are intended to be deployed and controlled to achieve equivalent or higher level of protection for workers, environment, and property (see Section 9)
- Share risk assessments that offer deeper details on how failure modes and consequences would be mitigated and handled (see Section 9)
- Suggest mitigation strategies for any operational constraints in regulations
- New jurisdiction mining companies could find it useful to create a project plan based on the Western Australia code of practice (Government of Western Australia Department of Mines and Petroleum, Resources Safety, 2015)
- Consider ongoing reporting requirements during operations

11. COMMUNITY AND SOCIAL IMPACT

Assessing the social impact of autonomy is critical because implementing autonomous systems changes labour needs. As a result, fear of job loss has been identified as a primary concern with automation. These issues affect not only employees but also other businesses and local communities that depend on the mine; a clear social licence to operate is necessary and engagement is critical. This section describes what to consider when engaging the workforce and community.

11.1 Engagement Plan

Those implementing autonomous systems should develop an engagement plan designed for listening to and addressing concerns. This plan will vary significantly based on whether the operation is a brownfield or greenfield one. For brownfield operations, the bulk of the engagement will often be about the changing work landscape. For greenfield operations, engagement strategies will focus on exploring the social benefits of automation for the community. The engagement plan should:

- Communicate a clear and consistent message
- Define the planned future state
- Develop a personnel plan that facilitates the transition from employees' current responsibilities to their new ones

A specific plan for engaging the community is also necessary. These actions demand a clear, strong, and aligned leadership to be effective. It would be helpful to collect some supporting case studies on the successes or failures of autonomous deployments in various environments to guide engagement (e.g., how well a specific product has been adopted by various organizations).

11.1.1 Evolving Workforce Requirements

Those implementing autonomous systems in brownfield operations need to address anxieties about how jobs will change. To do so, they must engage with the community, local workforce, and unions honestly and transparently to manage expectations. Leaders need to carefully evaluate their changing workforce requirements, the skillsets of the current workforce, and the actions to take. Changing workforce requirements include:

- Different skillsets needed (reskilling, upskilling, or new talent; see Section 11.2)
- Employee relocation (support and accommodation should be offered)
- Job loss (outplacement services should be considered)

In some situations, automation can prevent job loss or create new jobs. It can prevent job loss in situations where manual operations would no longer be feasible. For example, the potential for increased productivity with automation allows companies to mine lower-grade resources, making continued operations feasible. For greenfield operations or marginal operations, automation can allow financial investment where the manual equipment operations may otherwise close down or not be developed at all. Increased productivity from automation can also lead to job creation.

11.1.2 Communications Strategy

Communicating the overall social benefits of automation can help to engage the workforce and community. For example, automation is a safer approach in mining because it minimizes the exposure to hazards, which should be appealing to the community at large. The potential to work remotely can also provide flexibility and increase job satisfaction, especially for FIFO operations where it offers the opportunity to work closer to home (for more examples of benefits, see Appendix B). There needs to be a detailed communications plan for each stakeholder group, targeted to their specific needs. Consider communication methodology and engaging with a marketing or communications specialist (see Section 7.1).

11.1.3 Social and Economic Impact Assessment

Investigating the community's socioeconomic situation is essential. There may be existing agreements with the community regarding jobs and educational opportunities (e.g., agreements with indigenous communities concerning employment quotas). Plans must accommodate these agreements. The type of community determines how to perform the social and economic impact assessment and whether the degree of change affects the organization's social licence to operate. The degree of social impact will vary greatly depending on the type of operation or community. In FIFO operations where no local community is present, the changes would likely have little to no community impact. In less populated areas, small local communities may be dependent on the operation and be significantly affected. Larger regional communities could be less dependent on the operation but still be affected. A detailed list of steps to take and considerations for completing a social and economic impact assessment are in Appendix D.1.

11.2 Education

As autonomous methods become more common, shortages of specific new skillsets could make it difficult to operate the new systems. Those implementing autonomous systems need to invest in people and technology at the same time by playing a role in defining new skill requirements, providing educational opportunities to prevent skill shortages, and empowering the community at large.

The first step to defining needed skillsets is to complete staff assessments that identify the current skillsets, talent, and adaptability of the workforce. From there, identify the new skills required, and identify, promote, and possibly find the new skills pathways for individual employees and local or regional communities. Training pathways include:

- Retraining existing employees (most applicable to brownfield operations)

- Attracting, training, and retaining recruits using intrinsic motivators (e.g., job satisfaction) and, if sustainable, extrinsic motivators (e.g., high salaries)
- Determining opportunities for cross-training

Additional considerations include:

- Training timelines
- Training staff requirements
- How the work culture will change
- The growing role of contractors and service providers
- Collaboration with other departments and suppliers to develop and deploy solutions
- Collaboration with universities, colleges, and government to ensure that educational programs align with future needs of the industry (see Appendix D.2 for more information)

12. OPERATIONAL READINESS AND DEPLOYMENT

Introducing autonomous systems is a process that takes time to plan, design, and implement. Autonomous systems are complex, requiring those implementing them to integrate many layers of planning before deployment. While meticulous planning is needed, technological change is an ongoing process, and plans must also be adaptable to those changes. This section covers fundamental principles and considerations for implementing autonomous systems. This section discusses mine planning, engineering design, and architecture and covers essential deployment and commissioning activities.

The following factors need to be determined upfront, as the processes discussed in this section vary according to them:

- Why the organization wishes to automate a mine site (Section 8)
- The project scope and scale (what components to automate, what level(s) of autonomous system/equipment maturity to implement, and planned autonomous operational maturity); these choices dictate the necessary changes to the mine design and plan
- Implementation approach (Section 6.3)
- Technological approach (integration with supplier(s), mature technology, or new technology)

Fundamental principles or tenets for autonomous system planning and design activities are listed below. These principles must be considered throughout all stages from planning and design through to deployment and commissioning.

- Safety by design
- Systems thinking (consider how the mining value chain is affected by the decisions to automate, see Section 11.3)
- Open data (more modular, open, application programming interface [API] based; see GMG, 2016)
- Present and future needs
- Best practices rather than rigid design criteria (accommodating change)
- Customer first (define the customer and their metrics of value, see Section 8)

The processes outlined in this section are done concurrently with many of those described earlier in this document: change management activities (Section 7), the risk assessment (Section 9), ensuring regulatory compliance (Section 10), and evaluating social impact (Section 11). These processes also need to address cybersecurity requirements and intellectual property issues and incorporate interfaces and integrations.

12.1 Mine Planning and Design to Accommodate Autonomous Systems

Mine management and mine designers and planners should understand the limitations of the autonomous mining technology they will use and the differences between manual and autonomous operations (Appendix E.1). These differences influence designs and plans on many levels.

The physical mine, system infrastructure, and operational processes need to accommodate new characteristics of autonomous systems that require new approaches to excavation and material movement design. Ultimately, the mine design needs to be suitable for autonomous equipment and potential combinations of autonomous, semi-autonomous, and manual equipment; conventional designs for one or the other might not be sufficient. In greenfield projects or complete redesigns, the whole design can facilitate automation. In brownfield projects, current designs and operational processes need to be adjusted or redesigned.

All mine design and planning must incorporate safety by design. From the earliest stages, controls should aim to minimize the start-up risks with the systems (e.g., start simple and small and gradually build up capacity) and create an area where the autonomous system is isolated or interactions with manned mining systems are managed (e.g., consider the implications in mine design, plans, and schedules). Emergency management planning is also part of this process and is explored in Section 9.

12.1.1 Physical Mine Planning and Design

Mine designers and planners should ensure the physical mine design is suitable for autonomy, including:

- Work area, road design and construction that are in line with the system builder requirements (e.g., road surface, gradients, potentially harsh conditions)

- Traffic management (e.g., intersections, park-ups, load and dump locations, access controls for exclusion and interface areas)
- Mine geometry (e.g., pit shape, haul road width, tunnel profile, decline angle, bend and turn radius)
- Ventilation requirements (especially for underground mining)
- Infrastructure placement within the autonomous area (e.g., fuel facilities, crushers or ore passes, stockpiles, workshops and service areas, crib rooms, calibration and commissioning areas, services)
- Separate roads for manned light vehicles if possible, which can help reduce interaction

12.1.2 System Infrastructure Planning and Design

Supporting infrastructure and area requirements need to be identified early in the project. Considerations include:

- The autonomous system and associated infrastructure scalability and capability
- Equipment specifications, fleet size, and operating capabilities (e.g., turning circle, road network layout, gradient)
- Network communication infrastructure, especially critical in underground situations (e.g., wireless, fixed; see GMG, 2017a, 2017b, 2019c)
- Area access (e.g., location and control of area entry and exit points, provision of perimeter protection and signage)
- Monitoring system health (e.g., wireless, positioning systems)
- Location of remote operation and control rooms
- Automated system boundaries: whether the mine site can operate autonomously or whether there are additional communications infrastructure requirements, such as a backhaul internet connection for executing some automation services
- Managing electrical load and balancing demand
- Water management and dust control (especially in underground operations)
- Layers of control, including location and tracking of humans and non-autonomous equipment and other object detection and avoidance systems (reactive and predictive)
- OEM and OTM testing programs for autonomous system software/firmware updates and a mine-specific test system to ensure the viability of system software/firmware updates
- How changes integrate with non-mining external (e.g., urban environments) and internal (e.g., mill/processing plants) infrastructure

12.1.3 Process Planning

Mine processes change with autonomy: there are benefits to planning new processes from scratch, though there can also be modifications to existing ones. Considerations include:

- The sequence of activities that may change for a specific mining process
- Shift management and changeover
- New mining processes (e.g., continuous versus batch)
- Adjustments to the mining rate because of downstream material requirements, potentially minimizing rehandling and stockpiling downstream
- Situations and processes where people still need to be monitoring equipment (e.g., water drainage/dewatering pumps)
- Wait period following a blast for blast gas clearance before humans can enter the work area

12.2 Engineering Design Management Framework

To ensure successful delivery of an autonomous system, engineers must follow a robust and structured design management framework, considering specific design practices in connection with broader contexts. A strong design management framework improves OEE and enables safe and predictable production results by:

- Reducing safety risks and resulting delays
  - Embedding safety controls fail to a safe level of operations
- Maximizing asset availability
  - Minimizing breakdowns and failures
  - Allowing maintenance activities to be conducted within the planned hours
- Ensuring equipment utilization conforms to the plan
  - Minimizing production delays
  - Ensuring the mining equipment performs and delivers to production targets

Figure 5 presents key considerations for a design management framework for mining automation. Specific design considerations (technology assessments, design and engineering standards, functional requirements, functional safety, and maintainability) are at the centre and broader design contexts (communications infrastructure, human/system integration, environmental and social considerations and requirements, and local versus centralized decision-making) are towards the outside. Safety by design is central to all parts of the framework. Bidirectional arrows connect the points to show that all these considerations and contexts are interrelated.

Table 4 offers a non-exhaustive list of existing design standards that may be applicable.

12.2.1 Key Challenges

Key challenges to engineering design for autonomous systems are:

- Safety systems must be engineered, tested and commissioned in a simulated operational environment to be fit-for-purpose without compromising the productivity value driver.
- New and existing systems must be balanced in brownfield operations because downstream and upstream systems might require uplifts so that they can be successfully interfaced into the design.

Appendix E.2 provides further details on addressing these challenges.

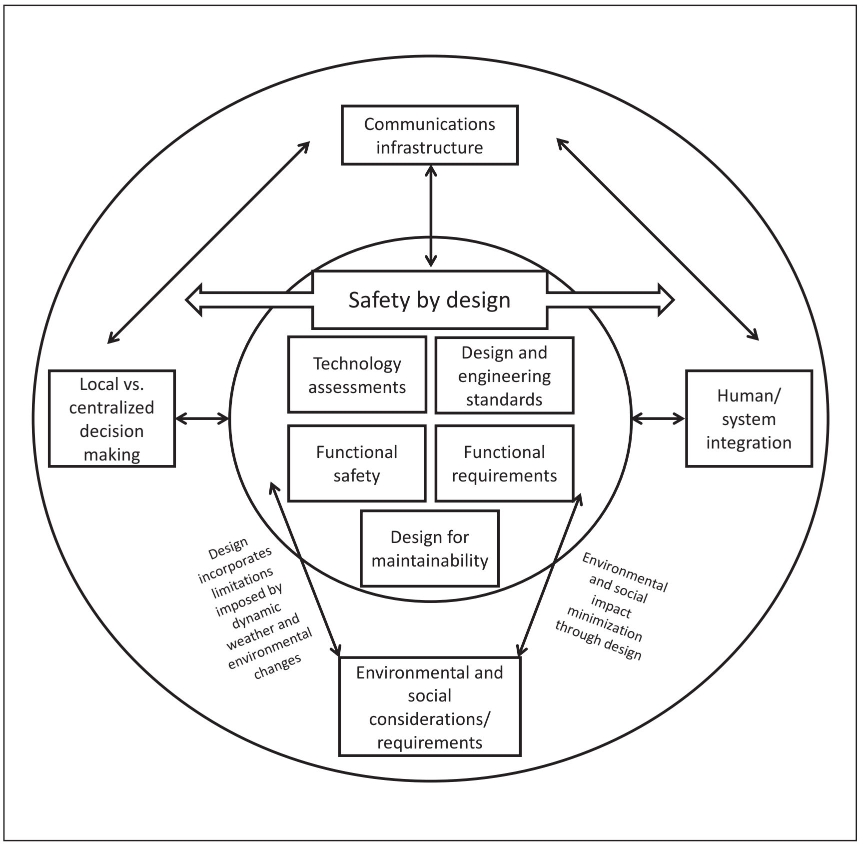

Figure 5. Engineering Design Management Framework for Implementing Autonomous Systems (Figure Design, GMG)

12.2.2 Design Management Plan

A design management plan must be developed and agreed upon by all stakeholders upfront (including the autonomous system supplier) and should include:

- Acceptance and performance criteria
- Agreement on how the design will be verified and approved (i.e., verification approach, quality management plans)
- Risk assessment approaches (see Section 9)
- A document deliverables list with both internal and external stakeholders (Appendix E.3)

12.2.3 Configuration Management

A comprehensive configuration management system must be employed for changes that are introduced through implementing autonomous systems, including:

- Operational and maintenance practices
- Design specifications
- System changes (e.g., software updates, upgrades, parameters) that affect mine design
- Data collection and integration
- End of life/obsolescence considerations for long-term installations
- Risk transformation

12.3 Architecture

Architecture refers to the structure, components, and design principles of a system and the relationships between them (International Organization for Standardization, 2011; The Open Group, 2018). Overall, the architecture for autonomous systems is an integrated IT/OT system: IT systems used for data-centric computing are integrated with the OT systems used to monitor processes and devices. Experience has shown that there needs to be an aligned IT/OT capability: most autonomous systems require a heavy reliance on both disciplines. Considerations around availability, redundancy, resiliency, and cybersecurity need to be addressed at every level of the architecture.

Architectures for autonomous systems need to be incorporated into the other design and planning processes outlined earlier in this section. Early on, roles and responsibilities required to develop the architectures need to be specified to ensure the appropriate skills and capabilities are in place.

Architectures also need to consider both the current and future state of the system. Reviewing emerging technologies is necessary to future-proof solutions and understand that new business value might arise in the future. Overall, the architecture should facilitate planning for future expansions and technology development and confirm that systems can be upgraded and expanded.

There several ways of categorizing architectures. Table 5 describes architecture in the context of autonomous

Table 4. Recommended Industry Design and Engineering Standards

Standard number	Title	Citation
ANSI/ISA-95.00.01-2010	Enterprise-Control System Integration—Part 1: Models and Terminology	International Society for Automation, 2010a
ANSI/ISA-95.00.02-2010	Enterprise-Control System Integration—Part 2: Object Model Attributes	International Society for Automation, 2010b
ANSI/ISA-95.00.03-2013	Enterprise-Control System Integration—Part 3: Activity Models of Manufacturing Operations Management	International Society for Automation, 2013a
ANSI/ISA-95.00.04-2012	Enterprise-Control System Integration—Part 4: Object and attributes for manufacturing operations management integration	International Society for Automation, 2012
ANSI/ISA-95.00.05-2013	Enterprise-Control System Integration—Part 5: Business-to-Manufacturing Transactions	International Society for Automation, 2013b
IEC 61508-1:2010	Functional safety of electrical/electronic/programmable electronic safety-related systems—Part 1: General requirements	International Electrotechnical Commission, 2010
ISO 13849-1:2015	Safety-related parts of control systems—Part 1: General principles for design	International Organization for Standardization, 2015a
ISO 13849-2:2012	Safety-related parts of control systems—Part 2: Validation	International Organization for Standardization, 2012
ISO 20474-1:2017	Earth-moving machinery –Safety—Part 1: General requirements (See also parts 2–10 for specific types of machinery)	International Organization for Standardization, 2017b
ISO 19296:2018	Mining—Mobile machines working underground—Machine safety	International Organization for Standardization, 2018a
ISO 17757:2017	Earth-moving machinery and mining —Autonomous and semi-autonomous machine system safety	International Organization for Standardization, 2017a
ISO 10007:2017	Quality management–Guidelines for configuration management	International Organization for Standardization, 2017c
ISO/IEC/IEEE 42010:2011	Systems and Software Engineering—Architecture description	International Organization for Standardization, 2011
ISO/IEC/IEEE 15288:2015	Systems and Software Engineering – System life cycle processes	International Organization for Standardization, 2015b
SAE J3016	Taxonomy of Terms Related to Driving Automation Systems	SAE International, 2018

Table 5. Architecture Subsets Applied to Autonomous Systems (continued on next page)

Category	Definition		Further details
	General	For autonomous systems	
Business	Drivers and processes that generate business value (see Appendix B)	Social impact, safety and organizational and operational readiness	Business impact assessment should be completed early to ensure the design is structured to meet business requirements for both systems and data
		"As-is" and "to-be" state for roles and responsibilities and reporting structures based on system interdependencies	See mining business reference model and exploration and mining business capability reference map (The Open Group, 2013, 2014).
Data	How the organization manages data	Required data baseline (plans for data capture, sensor data, measurement strategy) Scale (quantity) of data and data model (mapping where data are and need to go) Master data management and data quality management (including traceability of lineage) Alert monitoring (to quickly address issues with flow or quality) Data exchange considerations (often for large volumes at high speed/resolution) Data security, scalability, and validation Data standards (open/closed) Automated data surveys	Data streams to examine: • Operating physical data (operating logics) • Input operational data (commands and plans) • Technical services and design inputs • Optimization loops for production (localized and integrated optimization) • Equipment data (maintenance and operational) • Edge systems (safety, management, environment) • Localization and positioning information (to feed and from fleet management)

Table 5. (Continued)

Category	Definition		Further details
	General	For autonomous systems	
Technology	Software and hardware functionality, capability, and how they integrate with other processes	How existing technologies intersect with current data and application landscape Changes that will be necessary for meeting business needs with the new system Blocks of technology	Systems: • Basic input/output system • Solid communications network/fixed infrastructure (e.g., network link, network redundancies, consideration for protocols, considerations for latency) • Onboard autonomy system (automation processors) • Onboard detection/object avoidance system • Onboard machine actuation systems • Redundant power • Security systems

systems as they fall into the following subsets, as defined by in the TOGAF® standard (The Open Group, 2018): business, application, data, and technology.

12.4 Deployment and Commissioning

Deploying and transitioning to a new autonomous system requires careful consideration of:

- Proofs of concept
- Definitions of many KPIs and performance metrics
- Operating parameters
- Timelines
- Commissioning criteria

The system also needs validation and testing following an earlier formulated acceptance and commissioning strategy with a clearly articulated vision of the future.

A clear project execution plan should be developed that covers staging and timing, detailed and full deployment plans, and personnel needs. This plan should be formed based on the planning and design considerations presented earlier in this section and the chosen implementation approach (Section 6.3).

A systematic commissioning strategy is also required that covers the commissioning process, timeline, risks, roles and responsibilities, and test plan and meets formal approval and user acceptance. See Appendix E.4 for a more detailed commissioning activities list.

The implementation process must encompass a continuous improvement loop to feed back into the planning process. Keeping ongoing focus after commissioning is required for the system to allow for continuous improvement. The project closeout should include extensive field testing with key metrics measurement before final acceptance and commissioning.

13. FOLLOW-UP

Once the operation is commissioned and running, follow-up processes should continue. A transformation impact assessment should be conducted. Lifecycle and configuration management, conflict resolution management, and productivity optimization need adjustment. New maintenance regimes will need to be established, traffic flows might need adjusting, and plans for failed equipment recovery in an autonomous area of the mine site may also be needed. Operational KPIs should be reviewed once the system is operational. Moreover, geotechnical constraints may influence and be influenced by mine automation. Roles and responsibilities also need to be continually reassessed and updated to reflect ongoing changes.

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APPENDIX A: SAMPLE CHANGE MANAGEMENT MODEL

Established change management models can help guide the approach to the human change management for an implementation project of this complexity. There are many options: Kotter's eight-step change model (Kotter, 2012) is laid out below to illustrate what this might look like for the implementation of autonomous mining initiatives. These steps are at once sequential and parallel: they often overlap with and support one another.

Step 1: Create positive motivation for all participants to support the change

Generating inspiration and motivation to drive changes in behaviour, practices, routines, and processes is a key success factor in the human component of all change initiatives. This step is particularly relevant when building the case for implementing autonomous systems because the change will almost always affect the workforce. A strong change management program will need to find ways to focus all human participants on the positives associated with automation to overcome its negative association with job loss. Some of these will be part of business case, but more work is often required to help employees and others overcome their initial fears and begin to be motivated by the potential positives. It is also important to acknowledge that there will be changes for the local community and to respond transparently to their concerns. Providing positive case studies as concrete examples may help with this process.

Step 2: Form influential and powerful alliances

To reduce resistance to change, it is critical to engage with key influencers within management, the workforce, unions, the community, government, and other stakeholders affected by autonomous mining activities. These key influencers may or may not be those in formal positions of authority. Informal influencers often have the greatest capacity to undermine change, and effective change management works to understand the stakeholder landscape and its nuances. Simple top-down authoritative approaches to complex change are generally less effective. In contrast, broad alliances help promote and support change while also providing excellent feedback for anticipating and addressing concerns and resistance.

Step 3: Create a vision for change

Creating a compelling vision for the coming change is the most effective way to influence people and garner their support for the changes in the workplace. Visions must be desirable to all stakeholders. For those negatively affected by the changes, intelligent change management will seek to paint a picture of the benefits and new opportunities wherever possible while remaining transparent and acknowledging possible negative impacts.

Step 4: Communicate for vision

Clear, consistent, regular, and long-running communication is essential for achieving a strong platform for change. A thorough, disciplined, and exhaustive communications plan is required, ideally involving the broadest possible range of stakeholders.

Step 5: Remove obstacles

It is necessary to continually review and remove obstacles to change. Excellent change management constantly assesses the stakeholder landscape to ensure that potential problems and obstacles are being proactively monitored and managed. The change process is dynamic and often becomes more so as the change is implemented and becomes a reality.

Step 6: Establish short-term goals

Short-term goals and short-term wins keep employees motivated. Companies need to divide their complex processes into small, achievable chunks to motivate employees. Many businesses aim to become more agile when approaching change; this can be accomplished by breaking down what might seem overwhelming in scope into doable pieces and managing both investment and delivery risk by thoughtfully planning the work in stages. Intentionally celebrate small successes and build a winning culture along the way.

Step 7: Keep working

Business success requires constant effort. The change environment is dynamic because humans generally respond emotionally to change. The change management effort must be planned and executed with great discipline through to the end state. People should not be assumed to accept change until it is considered standard practice and process.

Step 8: Integrate change in the workplace's culture

Large change initiatives can lay the foundation for a company culture that expects and thrives on change, but this requires enormous discipline and focus on developing a consistently strong approach to managing change and seeing it implemented successfully. Change failures can not only result in the failure of the project but they can also impact the business's longer-term disposition toward further change. Thus, it is critical to manage change well to ensure the organization's long-term adaptability.

APPENDIX B: BENEFITS, VALUE DRIVERS, AND COSTS

Table B1 is designed for those developing a business case to consider which potential benefits, value drivers, and costs apply to their situation. It can also serve as a starting point for financial analysis and/or communications considerations. Please note that this list is not exhaustive and does not all apply to every situation. Further, because this is a holistic project, benefits and value drivers are often interdependent. For example, insufficient data analytics have the potential to reduce situation awareness with autonomous systems because the technologies that improve situation awareness (e.g., predictive maintenance) depend on their environment.

Table B1. Potential Benefits, Value Drivers, and Costs Associated with Implementing Autonomous Systems **(continued on next page)**

Area	Benefits	Value Drivers	Costs
Workforce			
Automation can change the size and shape of the workforce and alter specific roles, responsibilities, and skill requirements	More flexible locations possible with remote operation Improved work/life balance Improved diversity and inclusion (e.g., opportunity to hire people with disabilities or to implement more family-oriented strategies) Larger resource pool (new worker demographics will be interested in mining if jobs are cleaner)	Reduced personnel support costs for FIFO operations (accommodations, travel) Reduced employee turnover (relates to better conditions, more flexible locations, and improved work/life balance) Minimize the costs/effects of absenteeism Reduced overtime Easier to recruit people for better working conditions	Recruiting and offering incentives to attract and retain skilled labour (because of the current skill gap) Labour displacement, retraining and upskilling current employees, and training new recruits Change management (e.g., consultants, engagement) Government, regulator, or self-imposed community commitments
Health and safety			
Automation introduces new health and safety challenges and hazards, but it also reduces many of those associated with manned operations	Distancing operator from operation can lower exposure to health and operational hazards Better overall quality of life for workers Cleaner, less dangerous operating conditions (physical and mental health benefits)	Lower health and safety costs (e.g., those associated with work-related incidents) Lower fatigue management costs Lower lost time hours (from health and safety concerns) Lower accident repair costs Lower health- and safety-related insurance rates (lower human involvement and lower variability in machine operation)	Implementing new health and safety management procedures New physical infrastructure for physical separation, identifying autonomous areas, access points, control rooms Implementing new hazard controls New communications and digital infrastructure (e.g., for remote operations) Implementing layers of protection
Processes and technology			
Overall, autonomous systems change how mines operate. They can facilitate optimized mine design and consistent processes and can help minimize waste and improve overall planning processes.	More efficient mine design and processes (e.g., more efficient scheduling and traffic management) Consistent performance, leading to standardization and repeatability of operating practices New kinds of mining methods and equipment Preventive or predictive maintenance can lead to longer machine and machine component life	Long-term savings on mine design and structure Reduced productivity loss from process variability Decreased planned operator and equipment downtime (e.g., shift time delay, meal time) Reduced inter- and intra-cycle idle time Reduced non-value-added but necessary time (e.g., refuelling and maintenance stops) Reduced costs associated with equipment abuse/misuse and human-caused damage Optimized processes and increased communications capability can reduce wasted/inefficient time or unplanned downtime (e.g., shovel hang time, bunching, traffic conflicts, misdirected loads)	Time and resources for implementing design, scheduling, and safety management changes Required improvements to foundational technologies (e.g., radio, Wi-Fi®, LTE® network positioning) and geospatial technologies Constructing the physical environment for autonomy (roads, stockpile spaces, bypass and overpass roads, control rooms) Digital infrastructure and facilities (hardware, cloud provisioning, configuration, and commissioning) Technology development and maintenance Required incremental network improvements

Table B1. (Continued)

Area	Benefits	Value Drivers	Costs
Processes and technology (continued)			
These changes can translate directly and indirectly to increased OEE and productivity, reduced process variability, and long-term savings. All changes need to be identified and developed in a timely manner to maximize the success of introducing automation.	Increased measurement and control are often possible, increasing situation awareness Increased system integration Mining process will become closer to a continuous one Better coordination with downstream processes	Defer capital investment (by moving more material with the same equipment and extending the life of the equipment from autonomous operation versus manned operation. Improved efficiencies can also reduce the need to extend fleet size.) Lower machine maintenance costs (condition-based or predictive maintenance through instrumentation and monitoring versus a scheduled maintenance regime) Increase end-of-life asset (asset management to specification and through-life asset history capture will increase disposal value)	Required improvements to upstream and downstream equipment and processes Hardware or retrofit costs per machine Cost of handover Loss in productivity during ramp-up and deployment Equipment insurance Upfront and ongoing licence costs IT infrastructure and/or cloud platform maintenance and support, other technical support Ongoing subscriptions to usage-based service contracts Sensor change outs Maintaining the physical infrastructure Obsolescence

APPENDIX C: ADDITIONAL HEALTH AND SAFETY MATERIALS

C.1 Hazard Identification and Verification List

Hazard identification and verification systems can be implemented to quantify autonomous mining risks. They include, among others:

- A hazard and operability study (HAZOP) or control hazard and operability study (CHAZOP)
- Layers of protection analysis (LOPA)
- Functional safety analysis
- As low as reasonably practicable (ALARP)
- Bowtie analysis
- Task-based risk assessment
- Failure modes and effects analysis (FMEA)
- Employee hazard identification and reporting procedures and tools
- Workplace inspections
- Monitoring the working environment
- Change management
- Incident investigations
- Monitoring OEM and service company bulletins, recommendations and specifications
- Regulator safety alerts

C.2 Maintenance Hazard Controls

Maintenance hazard controls are especially important for autonomous equipment. To achieve the desired safety outcomes, maintenance activities for autonomous equipment should address:

- Safety-related parts of control systems and functional safety considerations for system maintenance (autonomous systems will not function without operational safety systems)
- Scheduled maintenance and inspections processes
- *In situ* inspection and servicing (e.g., consider ventilation for human traffic in autonomous areas during *in situ* work)
- Base platform autonomous components
- Recovery procedures in autonomous areas
- Maintenance area and activity isolation
- Condition monitoring and diagnostics
- Calibration and testing (including designated testing areas)

C.3 Preparing Personnel for Safe Work

C.3.1 Information

Personnel need to be informed so they are prepared to work safely and respond to any issues. This preparation includes providing the information necessary to complete tasks safely. Such information includes:

- Manuals, specifications and operating instructions provided by the system builder
- The operation's policies, procedures and plans
- Applicable legislation, standards, and other guidance material
- Identified hazards and their associated risks
- Historical incidents, near misses, and their documented resolutions
- Emergency shutdown procedures for autonomous equipment
- Training materials
- Ongoing identification of autonomous boundaries

Personnel must also be instructed about system functionality and specific tasks including the hazards and risks, the controls to be applied, and the job steps necessary to complete the tasks safely and correctly.

Tools such as safe work instructions or procedures and standard operating procedures may be used to document the process but should be reviewed and amended if there are any changes (e.g., to equipment or conditions). If there is to be a deviation from the safe work procedures, job safety or hazard analyses should be undertaken to capture the hazards and ensure controls are implemented and operational. Supervisory or management personnel must formally approve instructional tools. Establishing safe work practices is an administrative control (see Section 9.1.3). These are a secondary line of defence after higher level controls such as designing out hazards.

C.3.2 Training

Personnel must be competent in the tasks to which they are assigned; they must have the knowledge and skills necessary to perform the task safely and correctly. Competency is gained through training and experience while being supervised or mentored. Competency assessments should be based on evidence and verified before work commences. Competency verification must include a documented assessment. Competency can be verified by:

- Recognition of prior learning
- On-site recognition or validation of current competency
- Using the operation's training and development program

The risk management training provided must be appropriate to the assigned roles and responsibilities, and provide information on:

- The risk management process
- Task-specific safe work methods, including the safe use of equipment and safe systems of work

All personnel should understand the effects that their activities may have during commissioning, operation, and maintenance of the mobile autonomous mining system. They should also understand:

- What to expect if environmental or operational conditions change
- Site requirements for monitoring of machine performance
- How to recognize when machines are not operating as intended
- How to report incidents

Whenever systems of work or plant and equipment change or new systems of work or plant and equipment are introduced, there must be a system to ensure affected personnel are consulted, retrained and reassessed as necessary.

C.3.3 Supervision

Supervision is a fundamental safety function that complements information, instruction, and training provisions. Effective supervision sets and maintains high performance standards. Supervisors within an autonomous mining operation help achieve the operation's health and safety goals in a variety of ways, including:

- Leading and managing their team using their understanding of the key principles and safety features of the autonomous technology
- Ensuring work is carried out following system builder documentation
- Confirming workers (including contractors) are trained and verified as competent to perform their duties
- Communicating regularly with those affected by work
- Confirming fit-for-purpose equipment is available and used
- Monitoring the workplace and identifying and controlling hazards following site rules
- Confirming the operation's risk register reflects the risk analysis of jobs and critical tasks
- Reporting and recording performance issues (e.g., equipment failures, variances to approved operating parameters)
- Referring new and changed circumstances not covered in site rules to management for further instructions
- Communicating lessons from incidents

APPENDIX D: ADDITIONAL COMMUNITY AND SOCIAL IMPACT MATERIALS

D.1 Detailed Steps for Completing a Social and Economic Impact Assessment

The social and economic impact assessment determines the engagement strategy to take with the community.

1. Consider demographics and how they can influence the implementation project:
    - Population: Size, trends (growing or diminishing, native-borns or outsiders)
    - Age: Distribution, generational gaps
    - Cultural values: Education, remuneration, quality of life, mobility, family (understanding cultural values can help to explain how identity can be bound up to current manual skills and consider new replacement skills that are valued by organization and individual)
    - Economic situation: Employment rates, gross revenue, investment in the community, education and skills development, new startups
    - Education level: Skills, literacy, languages
    - Diversity policies: For example, those concerning ethnic groups and gender diversity (case studies can help guide this process)
    - The importance of the mine to local suppliers and towns: Both in the current state and future state.
2. Develop a community profile to determine how changing roles can be managed in specific situations. It can also help to determine what benefits the new technology can have for the community (e.g., it may attract new suppliers or attract visitors to the demonstration site). The current community situation needs to be compared with the feasibility study of the operation. The following details can be used to build a community profile:
    - Location: Remoteness, accessibility (transportation, presence of community)
    - Community history: Industry presence, evolution
    - Industry sectors and employers in the community: Both those depending on the mining operation (e.g., suppliers) and other industries
    - Infrastructure: Schools, colleges, utilities, hospitals, accessibility
    - Strategic community plans: Growth, population, sustainability, urban planning
    - Academic institutions: Strategic collaboration between academia and industry to stimulate simultaneous technological development and regional economic development and education
    - Unions: In the context of the local governmental rules and labour laws
    - Employment statistics: Including diversity (e.g., the status of women in the workforce), age, and education levels
3. Assess the outcome by asking the following questions:
    - What is the community's level of dependency on the mining operation, and how will it be affected by the introduction of automation?
    - Will there be a significant impact and for how long?
    - How can the introduction of the technology improve the community situation (e.g., mine life, new suppliers, visitors to demonstration site)?

D.2 Collaboration with Educational Institutions and Government

Mining companies should also work with universities, colleges, and government to ensure that educational programs align with the future needs of the industry. Working toward this in the short term, they can:

- Offer bursaries to students learning desired skills
- Provide students with relevant practical experience (e.g., hiring them through co-op programs, internships, summer jobs)

For more systemic educational changes, mining companies can work with universities, colleges, and government to:

- Redefine curricula in mining fields so they reflect the industry's future needs
- Define flexible pathways via staged qualifications in mining-related disciplines
- Encourage educational structures to change to provide more practical experience
- Educate and retrain teachers and instructors
- Establish globally relevant curricula, as there is more international mobility today

Potential future skills needed include (but are not limited to):

- Data analytics
- Machine learning/data science
- AI
- Robotics
- Optimization
- Automation
- Networking (transmission control protocol/internet protocol [TCP/IP])
- Wireless propagation and antenna theory (especially in an underground context)
- Other languages (for a more global industry)

APPENDIX E: ADDITIONAL OPERATIONAL READINESS AND DEPLOYMENT MATERIALS

E.1 Mine Design Comparison

Table E1 describes potential design differences between manual and autonomous operations.

E.2 Key Engineering Design Challenges

E.2.1 Safety and Productivity

Achieving the appropriate levels of safety without compromising the productivity value driver is a key design challenge. Safety systems that are too conservative, oversensitive, or prone to false positives (especially those at maturity level 3 where operator intervention is required for even minimal risk situations; see Section 6.2) regularly fail at a safe level of operation, increasing task variation, reducing utilization, and negatively affecting production performance targets. A safety system that is not rigorous enough, however, exposes resources to safety breaches, incidents, and regulatory risks.

Achieving the right balance can be accomplished by:

- Assessing, interpreting, and applying corrective actions for equipment OEM failure modes (i.e., braking, accelerating, steering, engine, hydraulics). The design must fully describe how all failure modes will be handled and how these will be tested to confirm the design. The design must correlate the autonomous system back to the equipment's safe working parameters.
- Incorporating an effective alarm management approach, ensuring data collected from alarms, alerts, and events are rationalized and that systems, processes, and roles are assigned to assess, interpret, and action them.

Table E1. Mine Design Difference between Manual and Autonomous Operations

Feature	Manual	Autonomous
Design layout	Designed using conventional design packages Design layout conforms with site-established parameters such as clearances, speeds, ramp angles, exclusion zones, angle of repose, and safety requirements	Can require separation of manned and autonomous operations Typically requires the same road widths as manned operations, but road widths must be accurate The design and area at loading and dumping locations will be to autonomous OEM specifications (similar to manned operations but may have different design requirements) Might prompt review of intersection designs, ramp angles, truck speeds, and traffic density Requires consideration for the interface between manual and autonomous fleets/operations Requires consideration for the maintenance interface Requires consideration for fuelling location and layout
Plans	Plans prepared at a functional level with the site supervisors/operators as the "customer"	Plans prepared at an execution level with the autonomous vehicle as the "customer," the vehicles operate exactly to plan Plans can be levelled and optimized in an autonomous environment
Planning	Planner prepares and delivers the plan of the day to the mine supervisors Supervisor executes plan using mining judgment and experience (supervisor can change loading/dumping locations and truck allocation)	Mine plan is uploaded into the autonomous operating system and the autonomous vehicles execute according to plan Planner requires feedback on plan effectiveness Supervisor does not have the discretion to modify the plan If there is a machine breakdown, the plan must be modified
Supervising	Supervisor primarily schedules and manages people	Supervisor primarily manages machines Supervisor must understand the mine plan and machine operating parameters
Controlling	Mine controller manages logistics within the pit	Mine controller oversees operations and manages the effectiveness of the operation Mine controller monitors autonomous vehicle operations and manages unexpected or inefficient operations Mine controller manages survey and dispatch changes

- Assessing cybersecurity threats and system vulnerabilities upfront and balancing them with the functional and safety requirements of the solution.

E.2.2 Balancing New and Existing Systems

It is challenging to balance new systems with existing ones. Unless the mine site is a greenfield environment, the mining equipment typically has existing onboard systems that need to be incorporated and interfaced into the design (e.g., fleet management system, high-precision global positioning system [GPS], asset health monitoring).

Upstream and downstream systems might also require uplift or improvements to interact with or support an autonomous system. These include:

- Improving communications network availability, reliability, throughput, bandwidth, latency, and coverage
- Identifying and removing single points of failure (i.e., components that, if they fail, halt the entire system) within the network
- Improving network routing, firewalls, and protocols
- Improving high-precision GPS availability, reliability, accuracy, and coverage
- Improving data centre availability, redundancy, and capacity
- Improving computer and storage availability, reliability, and capacity

E.3 Document Deliverables List for the Design Management Plan

Table E2 is designed to be a starting point: specific documents will vary depending on the situation.

E.4 Commissioning Activities List

To achieve the desired outcomes, commissioning activities for autonomous equipment should adequately address matters such as:

- System operator and system builder roles and responsibilities
  - Boundaries agreed upon, defined, and documented
  - Commissioning tasks assigned to competent persons
  - Formal commissioning and handover process
- Risk management process
  - Understand technology and specific functionalities
  - Identify hazards specific to commissioning phase (e.g., safety critical lists)
  - Ensure appropriate controls are in place
- Formal approvals process
  - System builders
  - System operators
  - Regulators
  - Other stakeholders as required
- Commissioning planning
  - Communications and reporting plan
  - Commissioning project plan and timeline
  - Select and survey suitable commissioning area (e.g., segregated, isolated)
  - Checklists for installation, assembly, and commissioning
  - Change management plan
- Commissioning test plan based on system builder recommended test procedures

Table E2. Potential Document Deliverables List for Inclusion in the Design Management Plan

Document deliverables
Risk management plan and assessments (e.g., HAZOP, FMEA)
Inspection and test plans
Audit schedules
Packing and shipping procedures
Quality management plan
Material listing and certificates (including hazardous materials)
Manufacturing data sheets
Engineering and technical specifications
Construction and installation specifications
Applicable standards
Asset management plans
General arrangement drawings
Detailed engineering drawings (including electrical/wiring/cabling drawings)
Equipment listing (mechanical, electrical, instrumentation, controls)
Installation, operation, and maintenance manuals
System architecture drawings
Interface control document
Configuration and logic files
Human-machine interface
Commissioning management plans and procedures
Performance testing and acceptance procedures
Commissioning test procedures
Vendor technical specifications
Network requirements
KPIs
Design management plan
Root cause analysis
Factory assessment
Stakeholder responsibility assignment matrix assessment overview

  - Safety systems tests
  - Operational performance tests
  - System integration tests
  - Documented test procedures
- Functional and user acceptance testing conducted in line with documented test procedures
  - Testing traceable to the system version or type to confirm systems meet system builders and operational requirements
  - Compliance with relevant standards
  - Test results are documented (e.g., pass, fail, defects, issues)
- System acceptance formal process for managing unresolved defects and issues
  - User acceptance based on system builder specifications
  - Training and competency assessment for various roles

APPENDIX F: LESSONS LEARNED

Below are examples of safety incidents that occurred at two mine sites, discussion of their root causes, and the lessons learned from them. For two additional examples from Western Australia, see: http://www.dmp.wa.gov.au/Documents/Safety/MS_SIR_226_Collision_between_an_autonomous_haul_truck_and_manned_water_cart.pdf and http://www.dmp.wa.gov.au/Documents/Safety/MSH_SIR_260.pdf.

In addition, a Safety Bulletin on "Seeking safe mobile autonomous equipment systems" is available at http://www.dmp.wa.gov.au/Documents/Safety/SRS-Publications-Mining_and_Explorations-Safety_Bulletin_110.pdf

F.1 Site A: Autonomous Loader and Personnel Interaction

Date: 21 April 2018

Region: North America

Incident: Autonomous loader and personnel interaction (no injuries)

CONTROL FAILURE

Vehicle/Pedestrian Interaction – Underground – Pedestrian Vehicle Segregation

- The mucking level was not properly cleared of personnel.
- The mucking level access barrier was not in place to prevent access to the level.
- Requirements for entering loading area were not followed.
- Safe operating procedures included lockout-tagout of barrier control panels when accessing levels, but was it unclear on specific uses in different situations.

ROOT CAUSE

Risk Management

- Global fatal risk control standards do not currently consider autonomous equipment.
- Requirements for contacting the loader operator were found to be inconsistent.

Change Management

- The change management process for implementing new technology in existing operations was insufficient.

Procedures

- Although the standard operating procedures and standard task procedures for autonomous operations were very specific, there were small discrepancies in the documents concerning testing the system within the exclusion zone.

LESSONS LEARNED

Risk Management

- An essential-factors process was undertaken and showed we must continue to look to replace administrative (people-based/behavioural-dependent) controls with engineering controls.

Monitoring and Measurement

- Administrative control risk mitigation for potential or known hazards requires frequent auditing for compliance and desired effect.

Fatal Risk Control

- There is currently no fatal risk management standard related specifically to autonomous operations.

Training and Awareness

- Accountability for personal behaviours must be consistent with policies and procedures.

F.2 Site B: Semi-Autonomous Loader and Personnel Interaction

Date: 27 June 2018

Region: Africa

Incident: Semi-autonomous loader and personnel interaction (no injuries)

Description of Event

Remote loading operations were being conducted with a semi-autonomous loader. Operations started after fixing a problem with the laser barrier, which had tripped and caused the loader to shut down. Another trip-out occurred, requiring the operator to inspect the work area before resetting the barriers, but the operator could not ascertain the reason for the trip. Mucking operations continued. While reversing from the draw point, the operator observed reflections on the rear monitor. He stopped but could not identify the reflections. As the operator turned to tram to the stockpile, he observed two people some distance away with the front monitor. He shut the machine off to investigate and found two production drill operators in the exclusion zone. Figure F1 presents a visual of this event.

CONTROL FAILURE

Vehicle/Pedestrian Interaction – Underground – Pedestrian Vehicle Segregation

- Separation and exclusion zone: The laser barrier was reset with personnel within the remote operation area.
- Personnel crossed the physical and electronic barriers while remote loading was in operation.

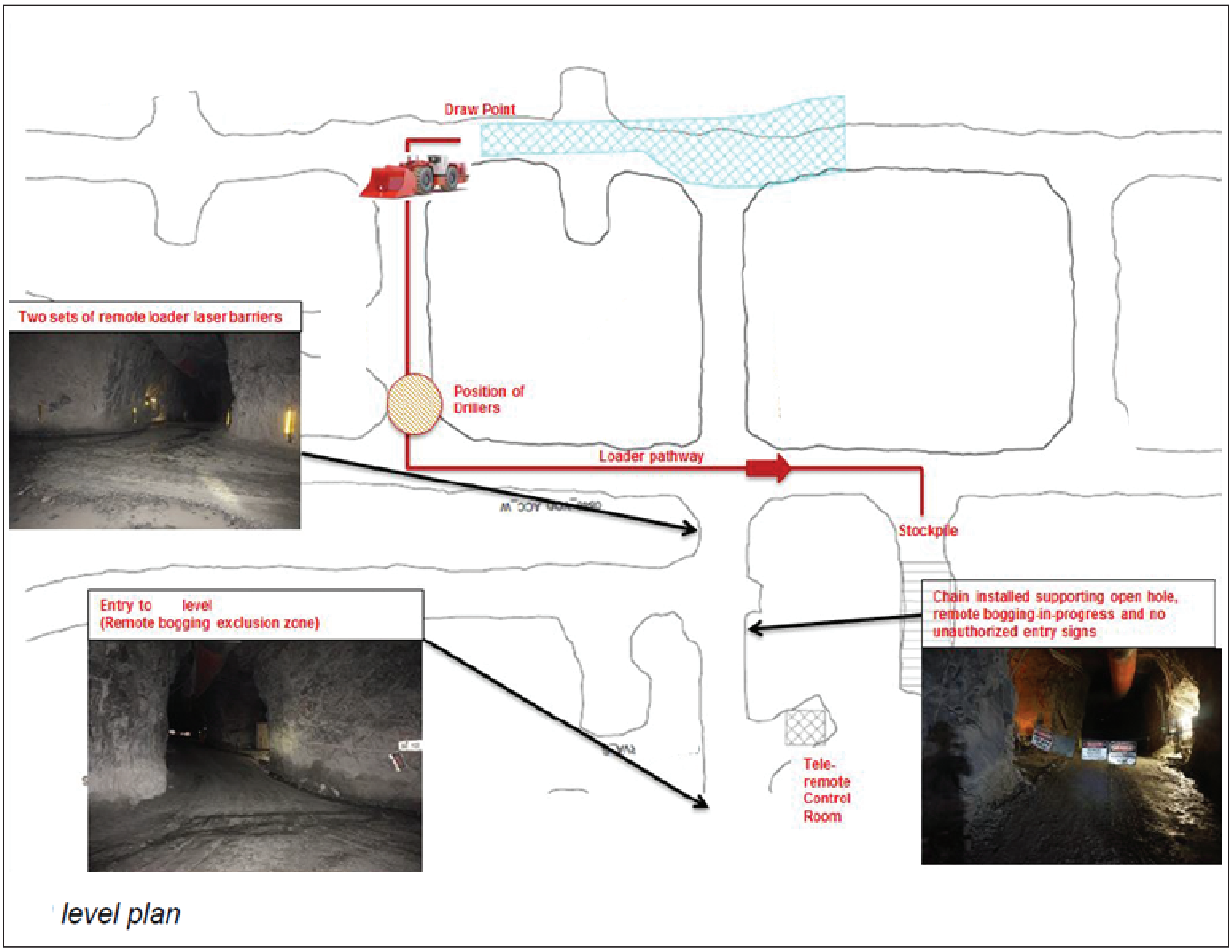

Figure F1. Visual of Semi-Autonomous Loader and Personnel Interaction (Provided by a GMG Contributor)

ROOT CAUSE

Organizational Culture

- The design and application of barriers allows them to be crossed for perceived authorized reasons.

Procedures

- The standard operating procedures did not provide sufficient guidance on managing multiple laser trigger events.

Design

- The laser system produced multiple false positives, diminishing the value of the control.

LESSONS LEARNED

Risk Management

- Replace administrative controls with engineering controls to eliminate/reduce behavioural dependency.

Change Management

- Standard operating procedures and training need to address all process changes, and personnel affected by that change need to be informed of how it could affect their work activities.

Fatal Risk Control – Vehicle/Pedestrian Interaction

- The reliability of the laser detection technology needs improvement to minimize false positive trigger events. Processes also need to be in place for escalation when multiple trigger events occur and for clearing the area prior to resetting the laser barrier.
- Visual and audible alarms when the laser detection is triggered need improvement.