AVALANCHE MITIGATION IN MINING INDUSTRY: BRIDGING SNOW SCIENCE, REGULATORY COMPLIANCE, AND TIME-CRITICAL DECISION-MAKING – A CASE STUDY FROM CODELCO ANDINA, CHILE

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ABSTRACT: Operating a large-scale mine (240kton refined copper for 2030) in the Chilean Andes confronts practitioners with a fundamental challenge: how to translate snow science into operational decisions that are not only technically sound, but also legally defensible. At Codelco Andina, there are more than 200 avalanche paths, thousands of workers travelling in and out of the operation, and critical infrastructure is exposed to avalanche hazard within a safety regulatory environment requiring traceability between hazard assessment, control measures, and documented outcomes. A persistent challenge is therefore the integration of advances in avalanche science with the governance requirements of industrial operations.

This paper presents an integrated framework that connects snow science, avalanche risk management, regulatory compliance, and time-critical operational decision-making. Bowtie analysis is used to formalize the relationship between avalanche threats, preventive and mitigative controls, and potential consequences, creating a structure that is both operationally functional and auditable. Decision thresholds derived from weather and snowpack monitoring are incorporated into operational management, allowing dynamic decisions concerning workforce exposure and access. Remote Avalanche Control Systems (RACS), structural defenses, and high-mountain helicopter protocols are integrated within the same risk management architecture. Climate variability, including atmospheric river events and El Niño conditions, increases forecasting complexity and requires explicit procedures for decision-making under uncertainty. The framework therefore combines technical assessment with defined operational thresholds, control ownership, verification, and documented evidence of effectiveness. Over more than 17 years of implementation, no avalanche-related worker fatalities have been recorded. Operational downtime in critical areas decreased from approximately 400 hours per year to zero, while the optimized mitigation strategy avoided approximately USD 45.7 million in capital expenditure through the incorporation of RACS into the design-engineering framework and the consequent reduction in the need for permanent structural measures.

The case demonstrates that avalanche science and regulatory accountability are not competing requirements. When integrated into a common operational framework, they can reinforce safety, traceability, investment optimization, and operational continuity in high-mountain mining.

KEYWORDS: Avalanche Management; Bowtie; Compliance; Operational Continuity, accountability.

1. INTRODUCTION

“Will an avalanche occur?” is only one of the questions that a large industrial operation must answer. The operational problem is more demanding: given the current hazard, exposure, controls, and operational requirements, what activity can safely continue, under which conditions, and with what evidence?

Avalanche risk management is traditionally associated with forecasting, snowpack assessment, and operational control. In large industrial operations, however, the decision to close an access route can therefore have consequences extending beyond immediate worker exposure, including interruption of production, logistical disruption, emergency response requirements, and significant economic losses.

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1.1 Operational Context

The operational context also creates a distinctive exposure pattern. Thousands of workers must travel through the mountain environment, while critical infrastructure and production systems may require continued availability during periods of elevated avalanche hazard. Consequently, the management system must simultaneously consider:

- Weather and snowpack evolution.
- Availability of mitigation systems.
- Emergency and aviation (air support).
- Operational and regulatory decision.

The fundamental operational question at Andina is not simply whether an avalanche will occur. The relevant question is whether, given the current hazard, exposure, controls, and operational requirements, a given activity can safely continue, under which conditions, and with what evidence.

An inadequate control may expose workers, while an unnecessarily conservative closure can interrupt critical operations and generate substantial economic consequences.

The management framework therefore seeks to avoid two undesirable conditions, treating avalanche risk solely as a scientific forecasting problem, or treating it solely as a compliance exercise. Instead, the scientific assessment must lead to an operationally meaningful decision, and the operational decision must remain traceable to the underlying hazard assessment.

2. GOVERNANCE FRAMEWORK

Industrial safety regulation requires identified hazards to be managed through defined and auditable controls. This creates an important governance requirement for avalanche management.

Traditional avalanche practice can rely heavily on expert judgment. Expert judgment remains essential, particularly when conditions are rapidly evolving, but it is not sufficient by itself to provide an auditable management structure for a large industrial operation.

The framework implemented at Andina addresses this issue by explicitly connecting four elements: hazard identification and characterization; control selection and ownership; operational decision making; and verification and documentation.

This creates a traceable chain from physical hazard to the operational outcome. The governance model does not attempt to replace avalanche expertise with administrative procedures. Rather, it provides an organizational structure in which technical expertise can be translated into decisions that can be communicated, implemented, verified, and subsequently reviewed.

This distinction is particularly important in complex events. A forecast may indicate increasing instability, but the management system must determine what that information means operationally. It may trigger increased monitoring, restriction of personnel access, closure of a corridor, activation of an avalanche control system, or preparation for a subsequent reopening decision. Each of these actions becomes a control that can be assigned, verified, and documented.

2.1 Risk management framework

Bow-tie analysis is a structured, visual method used to understand how a single risk event can occur and what consequences it may have. The diagram is shaped like a bow tie, with the central “top event” representing the moment when control over a hazard is lost. On the left side, potential causes or threats are displayed, while the right side shows possible outcomes or consequences.

The framework developed at Codelco integrates scientific assessment, engineered mitigation, operational controls, and governance into a common system.

2.2 Critical controls for avalanche risk management in industrial mining operations

The Río Blanco Valley has operated under a formal Snow and Avalanche Operations Manual (Atwater, M.N.) since 1965. This document undergoes annual revision and incorporates operational experience, lessons learned from fatal accidents within the avalanche profession, emerging technologies, and industry best practices. Through this continuous improvement process, Codelco Andina has identified the principal avalanche fatality risk scenarios and established a set of critical controls designed to prevent loss-of-control events and ensure operational continuity in a complex mountainous environment.

For avalanche risk, the approach allows the organization to identify avalanche initiation mechanisms, the avalanche event as a top event, and verification requirements for each barrier.

Bowtie analysis therefore becomes a bridge between avalanche science and industrial risk governance.

2.3 *Critical avalanche fatality risk*

1. Surface facilities within avalanche zones without territorial risk assessment. (Land use)

2. Non-operational or degraded avalanche early warning systems and Winter Operations Management Structure. (Staffing).

3. Snowpack and meteorological monitoring systems unavailable, degraded, or based on unreliable information.

4. Avalanche control activities executed with deficiencies in evacuation, exclusion-zone management, or communication protocols.

5. Unavailable or non-operational avalanche control systems.

6. Spontaneous avalanche occurrence affecting open operational areas where active mitigation measures cannot be applied or fail.

7. Intense rainfall events on a consolidated snowpack.

8. High-intensity snowfall exceeding forecasted conditions under climate patterns (El Niño).

2.4 *CC-01 Avalanche Hazard Zoning Applied to All Surface Facilities.*

Ensure that all permanent and temporary surface facilities are supported by a current territorial hazard assessment demonstrating that their location falls within an acceptable avalanche risk zone. This control aims to ensure that no personnel, equipment, or infrastructure is exposed to avalanche hazards without validated territorial risk controls approved by the responsible authority.

Verification: Approved records of avalanche exposure assessments for each permanent surface facility, validated by the responsible department and reviewed annually.

2.5 *CC-02 Operational Early Warning System and Winter Management Organization (staffing)*

Ensure that the avalanche early warning system and winter organizational structure remain current, operational, and supported by clearly defined responsibilities, Accountable Risk Owner. This control ensures clear responsibilities and accountable decision-making during winter operations

Verification: Official designation of Winter Operations Coordinators by department, confinement-duty managers, and staffing levels of avalanche specialists within the responsible area.

2.6 *CC-03 Snowpack and Meteorological Monitoring Supporting Daily Avalanche Hazard Assessments*

Snowpack and Meteorological Monitoring with Operational Instrumentation and daily danger and Risk Bulletin Issuance.

Ensure that avalanche specialists have access to reliable snowpack and meteorological information obtained through monitoring systems and field observations. This information shall be used to determine the Avalanche Danger Rating and support the daily issuance of the Avalanche “Risk” Bulletin (BDR). “Documentation of decisions and outcomes”

2.7 *CC-04 Preventive Avalanche Release Under Controlled Area Access Conditions*

Execution of Avalanche Release with Evacuated and Segregated Areas

Ensure that every preventive avalanche release operation is executed only after all affected areas have been completely evacuated, physically segregated, and formally released by the responsible area owner. This control prevents personnel and equipment from being exposed to artificially triggered avalanches.

Verification: Updated Avalanche Release Intervention Plan (PIDA) with clearly defined responsibilities and sector-specific roles, Annual review cycle.

2.8 *CC-05 Remote Avalanche Control Systems (RACS)*

Ensure that avalanche control systems remain available, and adequately maintained before and throughout the winter season, such that preventive avalanche release operations can be performed reliably whenever required.

• Annual maintenance program completed.

• RACS maintenance management process implemented, documented progress tracking and closure of all maintenance interventions.

• Operational explosive charges available for all systems.

• Inventory (Explosives / Gas) records maintained for each system, verifying quantities and operational throughout the winter season, including predefined critical stock levels.

• Critical spare parts available and validated.

• Inventory records maintained for critical spare components supporting avalanche control systems.

• Charge inventories verified and documented prior to each significant weather event.

The Maintenance Operational System **(SOMA)** is Codelco's corporate maintenance management framework, developed to standardize maintenance activities, improve equipment availability, and reduce operational costs. Its primary objective is to ensure that maintenance activities are performed under a consistent organizational standard, enabling efficient planning and controlled execution of maintenance processes.

2.9 CC-06 Avalanche Emergency Response, Search and Rescue Capability

Ensure that in the event of an avalanche involving buried or trapped personnel, emergency response measures are activated in a timely and effective manner through competent rescue teams, operational equipment, and victim localization technologies for rescue (reflectors). All response activities shall be conducted under a structured Incident Command System (ICS) with effective coordination among all participating organizations.

Verification

• Current Avalanche Emergency Response Plan.

• Avalanche search and rescue equipment.

• Minimum rescue team staffing.

• Certified competencies for rescue personnel.

• Emergency exercises and drills conducted on a regular basis.

• Reflectors distributed to exposed personnel.

3. NOTABLE EVENT OF WINTER 2026

Between 15 July and 3 August 2026, a sequence of storms affected the Río Blanco Valley, producing exceptional snow accumulations. resulting in sustained loading of the snowpack over nearly three weeks.

Period	Lagunitas (2750 m)	Open Pit (4000 m)
15-22 July 2026	439 cm	536 cm
23-29 July 2026	99 cm	109 cm
31 July-3 August 2026	95 cm	95 cm
Total	**633 cm**	**740 cm**

Table 1. Snowfall accumulation during July–August.

The maximum three-day snowfall occurred between 16 and 18 July, reaching 262 cm at Lagunitas and 299 cm at open pit mine. These values are particularly significant when compared with the historical avalanche database and design assumptions used by the Swiss Federal Institute for Snow and Avalanche Research (SLF) in the Lagunitas-Sur Sur Avalanche Hazard Map.

According to the SLF study, the largest historical avalanche cycles in the corridor were associated with snowfall totals of approximately 250-300 cm over 4-7 days, including major avalanche winters in 1963, 1965, 1974, 1983 and 2005.

The 2026 storm sequence exceeded these historical thresholds substantially. The 439 cm accumulated at Lagunitas during the principal storm cycle was approximately 1.5 to 2 times greater than the snowfall associated with the major historical avalanche events. Furthermore, the 262 cm accumulation in three days nearly matched the historical record of 270 cm snowpack increase in three days, identified by SLF as the largest observed value in the Lagunitas record.

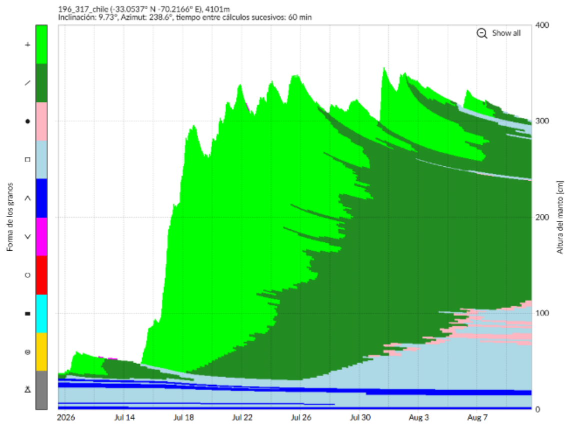

Figure 1: Snowfall accumulation during July–August 2026.

3.1 THE CENTRAL ANDES: SELECTED EL NIÑO WINTERS

The central Andes of Chile are characterized by strong interannual variability in winter precipitation and snow accumulation. In this high-mountain environment, extreme snowfall events can significantly affect access, transportation, infrastructure, and the continuity and safety of mining operations. Lagunitas meteorological station (2.765m.a.s.l.), located in the central Andes, provides a long term record of snow conditions in the region. Selected extreme winters from this record offer useful examples of the magnitude and temporal distribution of snowfall that mountain operations may face.

Within this broader operational context, selected extreme snow seasons from 1972, 1982, and 1997 are presented as historical examples of exceptional winter conditions associated with El Niño.

3.2 *SELECTED SNOW SEASONS*

The long term snow record at Lagunitas shows substantial interannual variability, including several winters with exceptional accumulation. Among them, 1972, 1982, and 1997 stand out as some of the most significant snow seasons in the historical record. Annual snow accumulation reached 2,142 cm in 1972, 2,023 cm in 1982, and 1,347 cm in 1997, representing approximately 191%, 174%, and 83% above their respective climatological normals. These values illustrate the magnitude that extreme winters can reach in the central Andes and provide useful historical references for high-mountain operational environments.

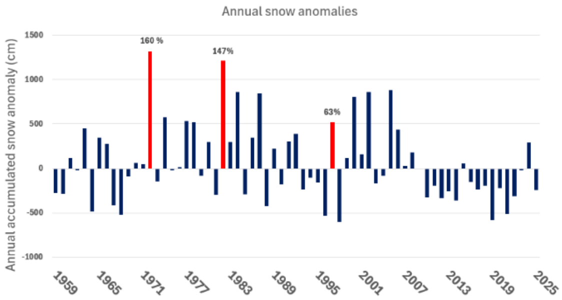

Figure 2: Annual snowfall accumulation anomalies at Lagunitas, highlighting the extreme winters of 1972, 1982, and 1997.

3.3 *ENSO CONTEXT*

The selected extreme winters occurred in association with El Niño conditions in the tropical Pacific. In central Chile, El Niño has historically been associated with an increased probability of wetter-than-normal winter conditions, although the magnitude and distribution of precipitation can vary considerably between individual events. The winters of 1972, 1982, and 1997 provide examples of this variability. Despite their common El Niño background, snow accumulation and its seasonal distribution at Lagunitas differed between the three cases. This highlights the importance of considering each winter individually and using large-scale climate conditions as context rather than as a direct predictor of local mountain impacts.

Final remarks. These historical cases show that extreme snow seasons in the central Andes can differ markedly in magnitude and seasonal distribution. This variability reinforces the importance of meteorological monitoring and forecasting to support high-mountain decisions that protect people, operational continuity, infrastructure, and critical assets.

4. CAPITAL INVESTMENT OPTIMIZATION

Integrated mitigation strategy also generated an economic benefit. Approximately USD 45.7 million in capital expenditure was avoided through optimization of the mitigation design.

A principal element of this optimization was the incorporation of RACS into the engineering framework, reducing the requirement to extend permanent structural measures in situations where active control could contribute to achieving the required risk-reduction objective.

This demonstrates an important principle for avalanche engineering in industrial environments: A system combining forecasting, operational controls, active mitigation, and selected permanent defenses can provide an alternative pathway to achieving an acceptable level of risk.

The incorporation of 14 RACS into the engineering design process was particularly relevant to capital optimization. Instead of relying exclusively on permanent structural measures, the design could consider a combination of active and passive controls. Andina operates approximately 100 RACS units.

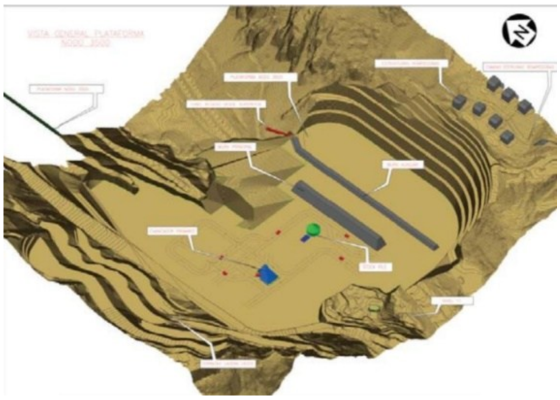

Figure 3: Baseline engineering concept before optimization (2015–2016), showing structures later reduced or redesigned to lower CAPEX.

Figure 4: Final as-built design, including a mechanically stabilized earth (MSE) wall optimized through the integration of RACS, designed for a 70 kPa impact pressure and commissioned in 2021.

4.1 *Original design concept and subsequent*

optimization at Node 3500

The original design concept for Node 3500, developed with the contribution of Hansueli Gubler around 2012, consisted of the following elements:

- 7 deflecting structures of 17m x 25m.
- Massive rock excavation of 16.300kton, down to elevation 3500m.a.s.l.
- A secondary dam of 10m high by 490m long.
- Retaining dam 32m high and 340m long.

This original concept was designed for a 100-year return period avalanche scenario, assuming no operational human intervention.

Following RAMMS simulations of multiple avalanche scenarios, the design was subsequently optimized through the incorporation of Remote Avalanche Control Systems (RACS). This allowed the engineering concept to consider a 30-year return period avalanche scenario together with active operational avalanche control and monitoring. The optimized design included:

- Massive rock excavation of 12.800kton down to elevation 3532 m.a.s.l.
- Retaining dam of 25m high by 270m long.
- 14 RACS units in redundancy. (Wyssen and Gazex).

This integrated approach produced a substantial improvement in operational continuity, reducing avalanche-related closure time from approximately 400 hours in 2005 to zero hours from 2021 to the present, including during the major winter event of 2026.

Figure 5: Mechanically stabilized earth avalanche dam providing permanent protection for the primary crusher against avalanche impacts.

It provides the greatest risk-reduction benefit. The result is an approach in which structural and active controls complement rather than compete with one another.

5. TIME-CRITICAL DECISION-MAKING

The operational value of an avalanche management system depends on its ability to convert information into timely action.

MONITORING → ASSESSMENT → THRESHOLD → DECISION → CONTROL → VERIFICATION → REOPENING.

At Codelco Andina, avalanche hazard assessment is supported by a specialized team of meteorologists and avalanche forecasters. The network includes 11 weather stations, four LIA® Laser Impulse Snow Height Acquisition units, 12 GINA® Geophones in Avalanches sensors, three IDA® Infrasound Detection System units, and AvalFox snowpack modelling. These data sources are complemented by regular stratigraphic snow profiles in the upper Río Blanco Valley. Together, they support the issuance of technical avalanche danger bulletins and operational avalanche risk bulletins that integrate control measures, exposure, and vulnerability. This framework ensures decision traceability, strengthens operational continuity, and prioritizes worker safety.

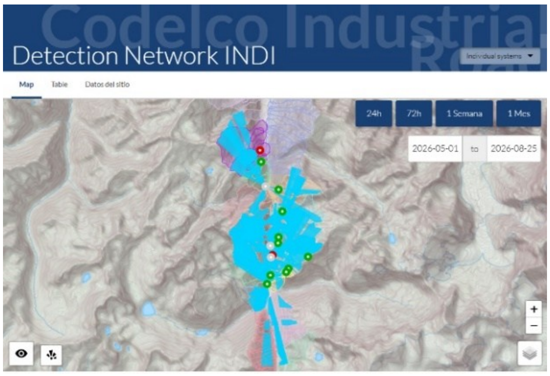

Figure 6: Avalanche detection-system network deployed along the mine access road corridor, locally known as the Industrial Road.

6. RESULTS

The implementation of the integrated avalanche-risk approach at Codelco Andina has produced measurable outcomes in safety, operational continuity, and capital investment.

6.1 Worker Safety

Over more than 17 years of implementation, no avalanche-related worker fatalities have been recorded. This result should not be interpreted as proof that avalanche hazard has been eliminated. Rather, it demonstrates the outcome of a long term system in which hazard assessment, operational decisions are continuously integrated.

Figure 7: Access to the concentrator plant, located in a high-avalanche-exposure sector.

Main access to the process area, flotation facilities, represents one of the most demanding operational sectors. Thousands of workers transit through this access on a daily basis, while continuous logistics and supply access are required to sustain copper-processing activities. Avalanche risk is managed through RACS, with monitoring by radar, LIA laser snow-height scanning, and geophones at the avalanche path."

6.2 Operational continuity

One of the clearest operational indicators is the reduction of downtime in critical areas. Operational downtime associated with avalanches decreased from approximately 400 hours per year to zero at Node 3500, including the run-of-mine (ROM) stockpile and primary crusher facilities.

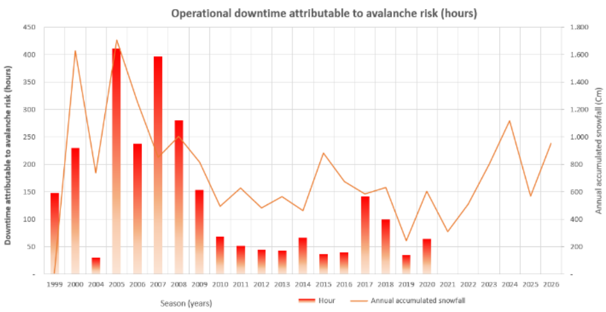

Figure 8: Operational downtime attributable to avalanche risk and annual accumulated snowfall since 1999.

6.3 Traceability

Traceability is critical in mining operations because it links hazard assessment, operational decisions, control implementation, verification, and outcomes into a documented and auditable process. This supports regulatory compliance, clarifies accountability, and reduces legal liability by demonstrating safety-critical decisions.

7. DISCUSSION

The Codelco Andina case illustrates a broader challenge in applying avalanche science to industrial environments.

In many avalanche-management contexts, technical excellence is evaluated primarily through the quality of forecasting, snowpack interpretation, or control operations. In large-scale mining, these capabilities remain essential but are insufficient on their own.

The organization must also answer: Who owns the decision? What operational threshold triggers action? What control is required? Has the control been implemented? How is its effectiveness verified? When can access be restored? What evidence demonstrates that the decision was justified?

The integrated framework addresses these questions by placing avalanche science inside a broader risk-management architecture.

This is consistent with the logic of Bowtie analysis, in which the effectiveness of risk management depends on the integrity of multiple barriers rather than on a single control.

The objective of integrated risk management is to identify the operational state that maintains an acceptable level of risk through a combination of controls. The results from Andina suggest that this balance can generate both safety and economic value.

There are, however, limitations to the transferability of this case. Codelco Andina has a particular combination of mountain terrain, organizational capabilities, technical expertise, infrastructure, and regulatory environment. The numerical results should therefore not be assumed to be directly transferable to another mine.

What is more transferable is the methodology. The conceptual architecture—hazard characterization, threshold-based decisions, Bowtie barriers, active and passive mitigation, operational controls, verification, and documentation—can be adapted to other mountain operations.

The case also demonstrates the importance of maintaining the connection between engineering and operations. An avalanche protection system designed without considering operational decision-making may fail to deliver its full value. Conversely, an operational avalanche program without engineering integration may become dependent on repeated reactive interventions.

8. CONCLUSIONS

Codelco Andina case demonstrates how avalanche science can be embedded within the governance and operational requirements of a large-scale high-mountain mining operation.

The principal contribution is not a new forecasting model or a new avalanche-control technology. It is the integration of existing scientific, engineering, operational, and governance capabilities into a common decision-making framework.

Bowtie analysis provides the structural connection between avalanche threats, controls, and consequences. Weather and snowpack information provides the scientific basis for operational thresholds. RACS, structural defenses, and helicopter operations provide complementary mitigation capabilities. Operational procedures translate these controls into workforce and access decisions. Documentation provides traceability and evidence of control effectiveness.

The reported results are significant, more than 17 years of implementation have occurred without an avalanche-related worker fatality. Downtime in critical areas decreased from approximately 400 hours per year to zero, while approximately USD 45.7 million in capital expenditure was avoided through optimization of the mitigation strategy and incorporation of RACS into engineering design.

These outcomes indicate that safety, regulatory compliance, and operational continuity should not be treated as competing objectives.

The principal lesson is that rigorous avalanche science becomes more valuable when it is translated into a governance structure that allows scientific information to generate timely, auditable, and operationally meaningful decisions.

For high-mountain mining, the future of avalanche risk management may therefore depend less on choosing between science and governance and more on integrating both into a single resilient operational system.

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