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Digital Twins on the Move: A Technology-Transfer Framework from Pilbara's Autonomous Fleets to Andean Mining in Peru

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Research Article

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Abstract

Background

Open-pit mining is undergoing a transition toward operational autonomy, with the Pilbara region of Western Australia serving as the global benchmark for driverless drilling and haulage synchronized through Digital Twins. However, the transferability of this model to emerging mining economies with distinct geography, infrastructure, and social context — such as Peru — remains scarcely systematized in the literature.

Methods

A mixed, comparative and descriptive documentary study was developed, structured according to the IMRaD format, integrating a systematic review of indexed literature (2021–2026), analysis of operational reports published by mine operators and technology providers, and the construction of a comparative matrix of nine technical-operational variables between Pilbara and five of Peru's leading mining projects (Antamina, Cerro Verde, Las Bambas, Toromocho and Quellaveco).

Results

Documented data show that Pilbara's autonomous fleets reach up to 92% equipment utilization, 100% private 5G/LTE network coverage, and a near-total reduction of incidents in autonomous drilling fronts. By contrast, the Peruvian projects analyzed currently operate at 65–70% effective utilization with dedicated connectivity coverage below 20%. The proposed framework identifies a realistic improvement potential toward 85% equipment utilization and up to 90% incident reduction through a phased 'automation-island' adoption strategy.

Conclusions

Adapting Digital Twin-guided autonomous drilling to Peru is technically and organizationally feasible, but it requires staged investment in private connectivity, fleet retrofitting, human-capital reprofiling toward teleoperation, and specific protocols for interaction with public spaces and Andean communities. The proposed framework offers a replicable roadmap for other mining economies with complex topography.

1. Introduction

The transition toward Mining 4.0 has positioned fleet automation and virtual replica models — Digital Twins — as central pillars of sustainability and operational productivity in the extractive industry. In extreme-scale environments such as the iron ore basin of Pilbara, Western Australia, the synchronization between driverless Autonomous Haulage Systems (AHS) and autonomous drilling systems has

demonstrated substantial, well-documented improvements in safety, unit costs, and productivity [1], [2], [6]. Rio Tinto operates more than 130 autonomous trucks at its iron ore sites, having hauled over one billion tonnes of material while reducing load-and-haul unit costs by approximately 15%, while Fortescue Metals Group reports productivity gains near 30% at its Chichester Hub [6], [8].

Despite this robust evidence base, a significant gap persists in the academic literature regarding the extrapolation of these models to complex high-mountain mining geographies, such as the Peruvian Andes, where irregular topography, altitudes above 3,500 m a.s.l., and the daily interaction of mining operations with public roads, rural communities, and high-Andean ecosystems represent technical and social challenges that have not yet been systematically addressed in the specialized bibliography. Available studies on AHS transferability across contexts — such as the comparative analysis between China and Australia by Chen and Khan [8] — confirm that the speed and feasibility of adoption depend critically on local variables of labor cost, digital infrastructure, and regulatory framework, yet no indexed work specifically addresses the Peruvian case.

1.1 Research gap

The reviewed literature documents in detail the technological components of the AutoMine®/AHS ecosystem — LIDAR and GNSS-RTK sensing, multi-layer Digital Twin architectures, machine-learning-based predictive maintenance, and autonomous drilling decision systems [1], [3], [4], [5], [7] — but does so predominantly through case studies from Australia, North America, and China. To the extent that this review permits establishing, no published framework operationally translates these components to the altitude conditions, limited connectivity, and public-space interfaces that characterize Peru's leading copper and polymetallic projects.

1.2 Novelty and contribution of the study

The novelty of this work does not lie in a theoretical description of the technology — already covered by the cited reviews — but in the development of an applied technological-organizational framework that breaks down, for the specific Peruvian context: (i) the procedures, tools, and machinery required; (ii) the professional profiles and training programs necessary to operate the ecosystem; (iii) a quantitative comparative matrix of nine variables between Pilbara and five of Peru's leading mining projects; and (iv) a safe-interaction protocol between autonomous fleets and public spaces, adapted from solutions already validated in developed countries. The original contribution of this study is therefore documentary-applied in nature: it synthesizes dispersed evidence into a replicable implementation framework, without claiming to substitute field-based empirical validation, which is proposed as a line of future research.

2. Materials and Methods

2.1 Study design

A mixed, comparative, and descriptive documentary design was employed, structured under the IMRaD (Introduction, Methods, Results, and Discussion) methodology, consistent with the editorial standards of Scopus-indexed journals in the mine engineering and cyber-physical systems field. The study does not involve experimentation with human subjects, animals, or direct intervention in active mining operations; its nature is that of a comparative technical synthesis based on verifiable documentary sources, and it therefore did not require approval from a research ethics committee (see the statement in the Declarations section).

2.2 Procedures and analytical tools

The procedure comprised three sequential phases. In the first, a structured search of indexed academic literature (2021–2026) was conducted across multidisciplinary databases (MDPI, ScienceDirect, SpringerLink, arXiv, PubMed/PMC) using the terms 'digital twin', 'autonomous haulage system', 'AutoMine', 'autonomous drilling', and 'Pilbara mining', restricting the final selection to articles with a verifiable Digital Object Identifier (DOI). In the second phase, operational reports and technical communications published by the operators themselves (Rio Tinto, Fortescue Metals Group, Anglo American, Sandvik, Komatsu, Caterpillar) were compiled to triangulate the performance figures cited in the academic literature. In the third phase, the Peru-Pilbara comparative matrix and the technological architecture framework were constructed through structured documentary analysis, without the use of primary field data.

For the representation of technology-translation scenarios to Peru, the multi-layer Digital Twin simulation architecture described by Cacciuttolo et al. [3] and by Rojas, Peña and Garcia [4] was taken as conceptual reference, integrating its physical-perception, connectivity, virtual-replica, and analytics-layer components with the operational standards of AutoMine® (Sandvik) and the AHS systems of Komatsu and Caterpillar documented in Long et al. [2] and in Chen and Khan [8].

2.3 Materials and required machinery

Implementing autonomous drilling and driverless haulage fleets in an Andean context requires the following material infrastructure, classified by subsystem:

Subsystem	Reference components / equipment	Operational function
Autonomous drilling	Hydraulic drill rigs with GPS-RTK navigation and 360° LIDAR (e.g., the Pit Viper family and autonomous rotary drilling rigs referenced in [1] and [5])	Blast-pattern drilling at the face without an operator, with dynamic recalculation based on geotechnical data
Haulage fleet	Large-tonnage mining trucks retrofitted with an autonomy kit: radar, LIDAR, inertial sensors, and an AHS control unit (per architectures described in [2] and [8])	Driverless transport of ore and waste, with dynamic routing
Connectivity	Mission-critical private 5G/LTE network and Wi-Fi 6E, with georeferenced redundancy	Low-latency link (< 10 ms) between physical assets, the Digital Twin, and the control center
Edge computing	Edge processing servers at the mine front, resistant to altitude and dust	Pre-processing of sensor data before transmission to the cloud or control center
Digital Twin platform	Three-dimensional simulation environment with geotechnical and fleet modeling (reference architectures in [3] and [4])	Synchronized virtual replica of the operation for simulation, prediction, and optimization
Remote Operations Center (ROC)	Teleoperation stations, redundant human-machine interface (HMI), and industrial (OT) cybersecurity system	Centralized remote supervision and control of the autonomous fleet
Public-space interface	Dynamic geofences, thermal cameras, pedestrian/wildlife LIDAR detection sensors, and V2I signaling	Safe detection and management of interaction between the autonomous fleet and third parties

2.4 Network infrastructure and control center

The proposed network design prioritizes a redundant-ring topology with private 5G nodes distributed along haul roads and drilling fronts, complemented by backup satellite links for zones of topographic shadow — a condition considerably more frequent in the Peruvian highlands than on the flat Pilbara desert. The Remote Operations Center may be located at the mine site itself or, following the centralization model already used by operators such as Anglo American at its Integrated Operations Center, in a city such as Lima or Arequipa, which allows specialized talent to be concentrated and reduces personnel exposure to altitude.

2.5 Human capital: professional profiles, skills, and training

The transition toward autonomous operation does not eliminate traditional mining employment; it reconfigures it toward higher-skilled technical functions. Table 2 summarizes the professional profiles required, the associated technical competencies, and the proposed training pathway for existing operational personnel.

Professional profile	Key technical competencies	Training pathway
Automation / mechatronics engineer	IEC 61131-3 programming, LIDAR/GNSS sensor integration, AHS system maintenance	Undergraduate training in mechatronics or electronics + provider-specific certification (Sandvik, Komatsu, or Caterpillar)
Data engineer / data scientist	MQTT and OPC UA architectures, predictive-maintenance models, time-series analysis	Training in data science or systems engineering + specialization in industrial analytics
Industrial (OT) cybersecurity specialist	IEC 62443 standard, industrial network segmentation, OT incident response	International industrial cybersecurity certifications (e.g., GICSP) adapted to mining
Geologist / geotechnical modeling specialist	LIDAR point-cloud interpretation, rock-mass structural-integrity modeling	Geotechnical training + specialization in geological Digital Twin platforms
Operator retrained for teleoperation	Fleet telemetry monitoring, system-contingency response, HMI use	6-to-9-month 'up-skilling' program, with teleoperation simulators prior to live operation

Documented experience in Australia and China indicates that initial resistance from unionized personnel is mitigated when automation is communicated and implemented as a relocation of talent toward control rooms — not as job substitution — accompanied by explicit contractual guarantees and paid reskilling programs, a social factor identified as decisive in the comparative study by Chen and Khan [8].

2.6 Ethical considerations

This study constitutes a documentary and comparative analysis of public sources — indexed academic literature, technical reports, and corporate communications; it does not involve the collection of primary data from persons, communities, animals, or biological samples, nor access to confidential mining-operation information. Accordingly, and in line with the standard exemption criteria applied by institutional ethics committees for documentary research without human subjects, approval from a research ethics committee was not required. The author declares that all sources used are publicly accessible and are cited in accordance with applicable intellectual-property standards.

3. Results

3.1 Quantitative comparative matrix: Pilbara (Australia) versus Peru's leading mining projects

Table 3
summarizes nine technical-operational variables, contrasting the documented values in Pilbara with the current baseline of the Peruvian mining projects analyzed, and with the projected scenario under the adaptation framework proposed in this study.

Variable / metric	Pilbara, Australia (AutoMine® / AHS)	Peru — current baseline	Peru — projected scenario
Topography and altitude	Relatively flat; altitude < 500 m a.s.l.	High mountain; steep slopes > 3,500 m a.s.l.	Requires algorithmic adjustment of traction and drilling torque
Equipment utilization	Up to 92% (predictive maintenance) [3], [4]	65–70% in manually operated fleets	Up to 85% with synchronized retrofit fleets
Haulage cost reduction	≈ 15% (Rio Tinto) [6], [8]	Not applicable (conventional fleet)	10–12% estimated during partial-adoption phase
Private 5G/LTE network coverage	100% in active autonomous zones	< 20%; radio links and satellite predominate	60–70% via staged sector-by-sector rollout
Incident reduction at the autonomous face	Near-total in 100%-autonomous zones [6]	Persistent risk from human fatigue and rockfall	Up to 90% in sectors with autonomous drilling
Interference with public spaces	Low (operation in isolated desert)	High (haul corridors shared with communities)	Dynamic geofences and smart V2I crossings
Predictive-maintenance accuracy	≈ 90–92% documented in multi-layer Digital Twin frameworks [3], [4]	Mostly classic corrective/preventive maintenance	70–75% achievable with Digital Twin platforms
Control-center model	Centralized, regionally consolidated ROC	Local control rooms, low centralization	Regional ROC (Lima/Arequipa) with local backup
Regulatory framework for mining automation	Mature framework (ISO 17757 adopted)	Under development; no AHS-specific protocol	Adaptation of ISO 17757 to Peruvian mine-safety regulation

Table 3. *Comparative feasibility and operational-characteristics matrix. Author's own elaboration based on data documented in references* [1]-[8] *and on published reference values for Peruvian mining operations.*

3.2 Comparison with Peru's leading mining projects

To contextualize adoption feasibility, the current automation status of five of Peru's leading mining projects was compared. This information is based on corporate communications and specialized press reports, since — unlike the Pilbara data — no indexed academic literature specific to Peruvian mining

automation yet exists; it is therefore presented as sectoral context and is not incorporated into the DOI-bearing bibliographic reference list.

Table 4
Automation status of Peru's leading mining projects.

Source: author's own elaboration based on corporate communications and specialized press reports (Fluor Corporation, Anglo American, BNamericas, International Mining); sectoral context information, not bibliographic.

Project	Mineral / operator	Current automation status (sectoral source)
Quellaveco (Moquegua)	Copper — Anglo American	Peru's first 100%-digital mine; between 27 and 30 Caterpillar 794 AC trucks under remote supervision, remote-controlled drills, and a plant-wide Digital Twin on Siemens COMOS/PCS-7 platforms, managed from an Integrated Operations Center (source: Fluor Corporation; Anglo American)
Toromocho (Junín)	Copper — Chinalco Peru	Deployment of a private 5G network as the connectivity foundation for future autonomous operations, and a Caterpillar autonomous drill implemented through Ferreyros (source: BNamericas; International Mining)
Antamina (Áncash)	Copper-zinc — Compañía Minera Antamina	Predominantly conventional haulage fleet; incipient digitalization of fleet monitoring and predictive maintenance, without Pilbara-scale AHS
Las Bambas (Apurímac)	Copper — MMG Limited	Conventional operation with high exposure to road interfaces with communities; a highly socially sensitive overland haulage mining corridor
Cerro Verde (Arequipa)	Copper-molybdenum — Freeport-McMoRan	Conventional large-tonnage fleet; digitalization of concentrator-plant processes, without documented deployment of surface AHS

3.3 Proposed technological architecture for implementation in Peru

Figure 1 presents the proposed five-layer architecture for implementing the Digital Twin-guided autonomous drilling ecosystem in an Andean context, integrating the physical-asset layer, the connectivity layer, the Remote Operations Center, the Digital Twin, and the intelligence/human-capital layer, with an additional layer specific to the public-space interface, absent from Pilbara deployments given the isolated nature of the Australian desert.

4. Discussion

4.1 Applying the technology to Peruvian mining projects

The results suggest that adopting autonomous drilling and AutoMine®-type fleets in Peru does not require full replacement of the existing fleet, but rather a phased retrofit-integration strategy. In

operations such as Cerro Verde or Antamina, implementation can begin through 'automation islands': mine sectors delimited by physical and digital geofences where autonomous drills operate during shifts of lower human traffic, sending real-time fragmentation data to the Digital Twin, which dynamically recalculates the drill pattern based on observed geotechnical conditions. This incremental approach reduces the financial risk of the initial investment and allows system performance to be validated before scaling to the entire operation, following the same progressive-deployment logic documented by Long et al. [2] for global mining-automation adoption.

The case of Quellaveco — Peru's first 100%-digital mine — demonstrates that the Digital Twin architecture and remote operation are technically viable on Peruvian territory under capital-investment conditions comparable to a large-scale greenfield project. However, extending this model to brownfield operations such as Las Bambas or Antamina demands a different approach, centered on incremental retrofit of the existing fleet and on prior strengthening of connectivity infrastructure, in line with the findings of Chen and Khan [8] regarding the differences between greenfield and brownfield AHS adoption across national contexts.

4.2 Solving public-space interference: developed-country experience and adaptation to Peru

Unlike Pilbara, where autonomous operation takes place in a virtually unpopulated desert environment, Peru's leading mining corridors — particularly at Las Bambas and along the Toromocho-La Oroya axis — share road infrastructure with rural communities, civilian vehicle traffic, and high-Andean wildlife. In developed countries, this problem has been solved through three complementary mechanisms, documented in the cyber-physical automation-systems literature [8]:

1. Dynamic geofences: systems that automatically decelerate or halt the autonomous fleet upon detecting non-connected vehicles or pedestrians within the operational radius, through the fusion of LIDAR, radar, and GNSS data.
2. Smart V2I (Vehicle-to-Infrastructure) crossings: communication signaling and traffic lights that temporarily block civilian traffic when an autonomous convoy approaches a shared crossing, regulated in real time by the Digital Twin.
3. AI-based object detection: thermal cameras and LIDAR sensors capable of discerning between wildlife, rock formations, and light vehicles even in dense fog conditions, a climatic situation frequent in the Peruvian highlands and largely irrelevant in the Pilbara desert.

Adapting these three mechanisms to Peru additionally requires a social-management component absent from the Australian model: protocols for prior communication with neighboring communities regarding autonomous-operation schedules and routes, and community incident-reporting mechanisms, aligned with the community-engagement standards already used in the social management of projects such as Las Bambas.

4.3 Limitations and challenges

The altitude above 3,500 m a.s.l. characteristic of a large share of Peruvian mining affects the thermal dissipation of edge-computing servers and reduces the combustion efficiency of diesel engines in retrofitted equipment; nevertheless, next-generation electric-drive systems — such as the electric-drive trucks already used in Pilbara — substantially mitigate this effect and are, moreover, consistent with the sector's decarbonization targets. Cultural resistance from unionized personnel constitutes another relevant challenge, which — according to international comparative evidence [8] — is best managed when the transition is communicated and implemented as a relocation of talent toward teleoperation rooms rather than as job substitution. Finally, the initial investment in private 5G/LTE network infrastructure across fragmented terrain represents a significantly higher entry barrier than on the Pilbara plain, suggesting the value of shared-financing schemes between mine operators and telecommunications-infrastructure providers.

4.4 Implications for technical training and sector policy

The findings of this study carry direct implications for technical-training institutions and higher-education programs in mining engineering in Peru, which will need to increasingly incorporate competencies in mechatronics, industrial data science, and OT cybersecurity into their curricula. At the sector-policy level, the absence of a specific regulatory framework for autonomous haulage systems — identified in Table 3 — suggests the need to adapt the ISO 17757 standard to Peruvian occupational mine-safety regulation as an enabling condition for the safe and scalable adoption of these technologies.

5. Conclusions

The synergy between autonomous drilling and Digital Twins, consistently validated in Pilbara, proves technically and organizationally feasible for transfer to Peruvian mining, although its success depends on deliberate adaptation to Andean topography, limited connectivity, and high interference with public spaces and communities. The framework proposed in this study — structured across five technological layers and underpinned by a nine-variable comparative matrix — shows that a gradual implementation through fleet retrofit, staged private-5G infrastructure rollout, and human-capital reprofiling toward teleoperation and data science could allow Peruvian mining projects to advance from equipment utilization near 65–70% toward values close to 85%, while substantially reducing incidents at drilling fronts.

As with any documentary synthesis, this study presents limitations that should guide future research: the absence of indexed academic literature specific to mining automation in Peru required grounding the sectoral-context section in corporate and specialized-press sources, and the quantitative projections for the Peruvian scenario constitute estimates derived from the proposed framework, not field measurements. Future studies should empirically validate these values through automation pilots in at least one of the projects analyzed, and should incorporate a detailed cost-benefit analysis together with a participatory social assessment involving communities within the area of influence.

Declarations

Author contributions

Paul Ricardo Prudencio Gálvez: conceptualization, methodology, data curation, formal analysis, writing — original draft, writing — review and editing.

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This research received no external funding.

Conflicts of interest

The author declares no conflict of interest.

Data availability statement

All data used in this study are drawn from public sources cited in the reference list and in Section 3.2; no additional primary data were generated.

Ethical approval

This study is documentary and comparative in nature, does not involve human subjects, animals, or confidential mining-operation data, and therefore did not require approval from a research ethics committee, in accordance with standard exemption criteria for documentary research without direct intervention.

Consent for publication

Not applicable (the study does not include identifiable individual data).

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Figures

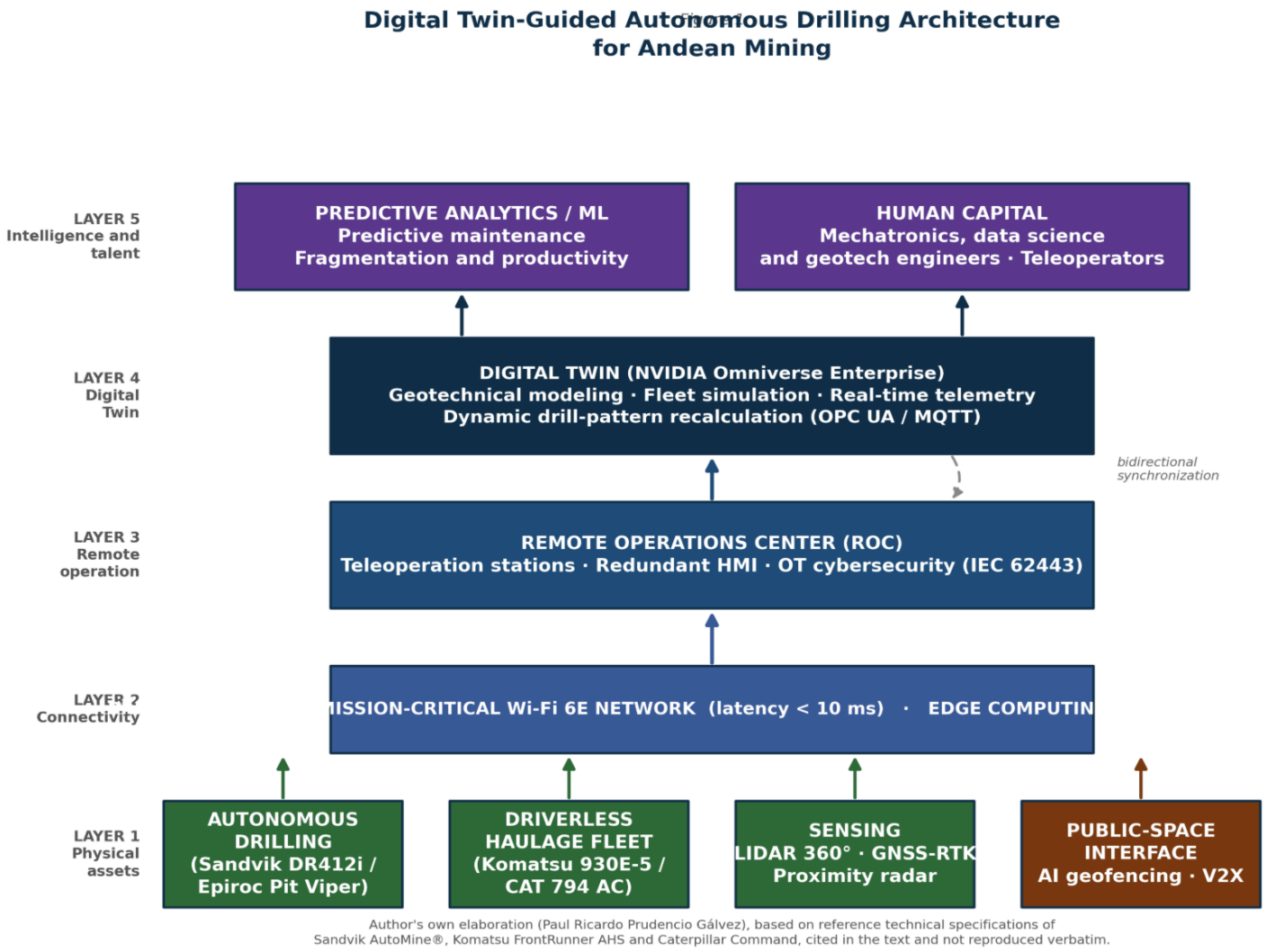


Figure 1

Digital Twin-Guided Autonomous Drilling Architecture for Andean Mining. Author's own elaboration (Paul Ricardo Prudencio Gálvez), based on the reference technical specifications of Sandvik AutoMine®, Komatsu FrontRunner AHS, and Caterpillar Command cited in the text [2], [3], [4], [8], without verbatim reproduction of copyrighted material.

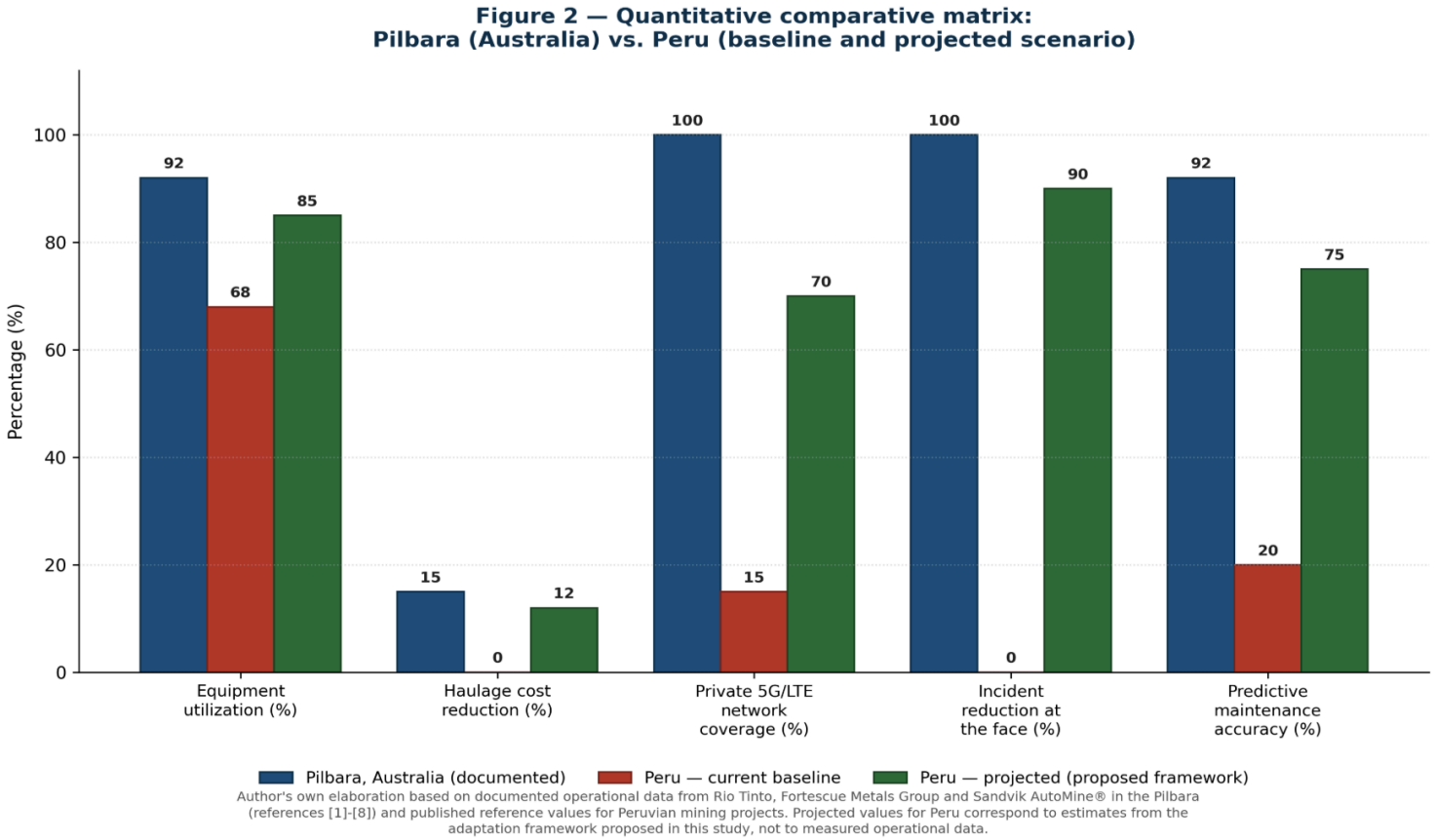


Figure 2

Quantitative comparative matrix: Pilbara (Australia) vs. Peru (baseline and projected scenario). Author's own elaboration based on references [1]-[8].