NTT DATA

HAULAGE · ENERGY · OPERATIONAL DIGITAL TWINS

Beyond Productivity

The Digital Twin that Co-Optimizes Energy and Production in High-Altitude CAEX Haulage

Why the systems dispatching your fleet optimize the wrong thing — and what changes when energy enters the decision, in real time, without slowing production

AUDIENCE	FOCUS	REGION
Operations, Energy & Reliability	Energy + production in haulage	LATAM · High-altitude copper

Priscila Alves · Natural Resource Manager · NTT DATA Chile · **Víctor Baeza** · Senior OT Architect · NTT DATA Chile

Contents

01

EXECUTIVE SUMMARY

In an open-pit mine, ore haulage is the site's largest energy consumer — and the decision that moves it most is made by a system that does not look at energy. That is the opportunity, and it is the thesis of this paper: an operational digital twin that **co-optimizes production and energy inside the same decision, in real time**, cut energy per tonne by **6.4% in simulation while conceding just 1.8% of cycle time**. Not energy *or* production. Energy *and* production.

The distinction that matters to an executive is one of kind, not degree. The digital twin most of the industry talks about is one that *shows*: a replica that visualizes fleet status. The one we propose *decides*: it closes the loop and hands operating recommendations back to the dispatch system. That difference — observing versus acting — is what separates a dashboard project from an optimization project, and it is where the optimization value sits.

In our experience supporting high-altitude operations, the most surprising thing is not the size of the available energy saving: it is that nobody was measuring it inside the dispatch decision. Energy is reported, audited, presented to the board — but it does not feed back into how each truck climbs each cycle. Energy is information, not control.

We will be direct about the state of the evidence, because honesty is part of the argument: these results come from **calibrated physics simulation, not a deployed operation**. We say it plainly because, for an operator who has watched "optimization" projects fail, knowing where a model does *not* win is what builds trust. The pages that follow explain where the energy sits, why altitude makes it worse, what exactly this digital twin does, what the simulation showed — including its limits — and, above all, what an executive should demand before signing the next "fleet optimization" project.

> **KEY INSIGHT —** Haulage is the mine's biggest energy lever, and the decision that moves it most is made by a system that cannot see it. Closing that gap is not another dashboard: it is putting energy inside the decision, cycle by cycle.

02

THE ENERGY DISPATCH DOES NOT SEE

When an operation talks about its energy consumption, haulage should be the first line of the budget, not a footnote. In Chilean open-pit copper mining, **loading and haulage consume close to 75% of the energy of the extraction process**[^energy]. Globally, haul trucks concentrate more than 30% of an open-pit mine's energy and more than half of its direct emissions — Scope 1[1].

The asymmetry is the point. Energy is the largest line item and, at the same time, the one that least enters the minute-by-minute decision. This is not carelessness; it is how the operation is organized: the systems that dispatch the fleet — Fleet Management Systems (FMS[2]) and Autonomous Haulage Systems (AHS[3]) — were born to optimize productivity, and energy is attacked in another lane, as an electrification or powertrain project. In practice they are **two teams that do not talk to each other**: the one deciding each cycle's speed does not have energy in its objective, and the one managing energy does not touch real-time dispatch.

> **KEY INSIGHT —** Optimizing haulage for productivity alone leaves the mine's biggest energy lever out of the decision.

That arrangement produces a local optimum with a hidden cost. A dispatch that chases only the shortest cycle time, with fixed per-segment speed profiles and no energy feedback — the typical industry configuration — makes decisions that are optimal for the stopwatch and expensive for the energy meter. And, as we will see, there is one place where that difference stops being linear.

[1] Direct greenhouse-gas emissions from sources the operation owns — in mining, above all the diesel burned by mobile equipment — under the GHG Protocol.

[2] Fleet Management System — the system that assigns and dispatches the haul fleet in real time, optimizing truck-shovel assignment, queues and cycle times.

[3] Autonomous Haulage System — the system that operates haul trucks autonomously, with its own speed envelope and safety constraints.

03

WHY ALTITUDE CHANGES THE ARITHMETIC

Everything above is true at sea level. In the copper operations of northern Chile — Tarapacá and Antofagasta, between 3,000 and 4,600 meters — it gets worse.

With less oxygen, diesel engines deliver less power and run hotter. Modern ultra-class trucks come with high-altitude packages that let them operate in the cordillera with no formal power derating, but “no formal derating” is not “no physical cost”: thin air raises exhaust temperatures and the thermal stress on the traction system, even in equipment rated for altitude.[4] Altitude does not change the direction of the energy problem; it changes its slope. Every speed and load decision on a ramp costs more, and the margin between operating efficiently and punishing the asset is narrower.

That is why high-altitude copper is the perfect edge case for rethinking how energy is dispatched. It is not an abstract laboratory: it is where the industry is building, today, its next generation of haulage infrastructure.

04

THE RAMP: WHERE PRODUCTION AND ENERGY FIGHT

Take the scenario the model evaluated, representative of a real high-altitude copper operation: trucks of 320 to 360 tonnes payload climbing a 2.1-kilometer segment at 9-10% average grade, with trolley[5] coverage near 65%, at an elevation of 2,800 to 3,200 meters.

On a flat segment, asking for a little more speed costs a little more energy: the relationship is smooth, and the stopwatch and the meter barely argue. On a high-grade ramp, that relationship breaks. Energy becomes non-linearly dependent on three things that compound — the truck’s payload, the segment’s gradient and ambient conditions. Pushing a nearly full truck a little faster up a steep ramp does not cost “a little more” energy: it costs much more, and it pushes the drivetrain toward its thermal stress zone.

This is where productivity-driven dispatch fails silently. Optimizing cycle time, it picks the speed that minimizes seconds — and on the ramp that choice **over-prioritizes throughput exactly where the energy penalty is steepest**. It is not a configuration error: it is the logical

---

[4] Industry rule of thumb: naturally aspirated diesel engines lose on the order of 3.5% power per 305 m of altitude. Ultra-class high-altitude packages (HAA) compensate the power, but thinner air still raises exhaust temperatures and thermal stress.

[5] Trolley assist — electrification of a ramp segment via catenary and pantograph, letting the truck climb on grid electricity instead of diesel. CAEX is the Chilean-mining term for the ultra-class haul truck (over 300 tonnes payload).

consequence of optimizing a single variable at the point where the other one spikes. The system is doing exactly what it was asked to do; what it was asked to do is incomplete.

> **KEY INSIGHT —** On ramps, energy is non-linear in payload, grade and environment. Conventional dispatch pays invisible penalties there, not through error but by optimizing a single variable where the other one spikes.

An experienced operator senses it and sometimes corrects it by hand. But that correction does not scale to an autonomous fleet of dozens of trucks running around the clock, and it is not in the objective of the system that decides.

05

THE TWIN THAT DECIDES, NOT THE ONE THAT DISPLAYS

Here is the distinction that orders everything else. "Digital twin" gets used for almost anything, almost always to describe a screen: a replica that shows an asset's state. That is not the twin in this work.

> **KEY INSIGHT —** The twin that matters is not the one that shows. It is the one that decides.

The twin we propose closes the loop: it reads the operation, computes the best play and hands it to the dispatch system as a control recommendation. Concretely, it does three things. First, it understands the physics of why it costs what it costs to haul a load up a gradient at 3,000 meters — not black-box statistics, but an energy model built on the real forces of the problem.[6] Second, it fuses in real time three data families that live apart today: truck telemetry (payload, speed, engine power), road geometry (grade, curvature, surface condition) and the state of the electrical infrastructure (trolley availability, grid power constraints). Third, on that basis it decides: it modulates speed within a safety-bounded range, adjusts when it pays to hook onto the trolley, and rejects a load cycle when it detects an overload that would trip thermal thresholds. The decision is remade continuously, in 30-second windows.[7]

[6] Technically, a tractive-effort model summing rolling resistance, grade resistance and altitude-corrected air density, extended with a dynamic thermal-load estimator for the traction system.

[7] This is model predictive control (MPC): it optimizes actions over a short receding horizon — here, 30 seconds — and re-solves continuously with each new data point, inside the AHS speed envelope (modulation bounded to ±10%).

The difference matters to the buyer. A twin that visualizes needs screens and people to watch them. A twin that decides needs integration with the control systems and a validated safety envelope. They are different projects, with different risks, and confusing them is the most common way to buy an expensive dashboard believing you bought an optimization.

06

THE EVIDENCE, IN SIMULATION

One clarification up front, because it sustains the credibility of everything else: the results that follow come from a **calibrated physics simulation** built on published operational data for ultra-class trucks in high-altitude copper — not from a deployed operation. The model shows this; taking it to the field is the next step, and Section 09 says what that demands.

Over multiple haul cycles, varying payload, grade and environment, we compared the digital twin against productivity-driven FMS dispatch. This is the table.

Table 1 Comparative performance between productivity-driven FMS dispatch and the closed-loop digital twin, over multiple simulated haul cycles (2.1 km ramp at 9-10%, 2,800-3,200 m).

Metric	FMS (baseline)	Digital twin	Change
Energy (kWh/t)[8]	100%	93.6%	−6.4%
Cycle time	100%	101.8%	+1.8%
Cycle-time variability	100%	95.3%	−4.7%
Thermal stress events	100%	92.4%	−7.6%

The headline is energy: **6.4% less per tonne hauled**, with peaks of up to **9.1% on ramps above 9% grade** — where it hurts most. The cost of that gain is modest and under control: average cycle time rises 1.8%. And here is the interesting part: cycle-time *variability* goes *down* by almost 5%. Lower variability means more predictable haulage, easier to synchronize with the shovel and the crusher. The twin does not destabilize production; it stabilizes it.

There is a third effect, on the asset: thermal stress events on the traction system fall 7.6%.[9] Optimizing energy, in this model, also protects the drivetrain — a benefit that never shows on the energy meter but does show in the reliability budget.

[8] Kilowatt-hours per tonne — energy consumed per unit of material hauled; the energy-efficiency metric of haulage.
[9] Thermal stress event: the traction system operating above 85% of rated capacity sustained for more than 90 seconds.

KEY INSIGHT — In simulation: 6.4% less energy per tonne conceding just 1.8% of cycle time, with variability down almost 5% and thermal events down 7.6%. Energy and production stopped competing.

07

THE MODEL'S HONESTY: WHERE THE GAIN YIELDS

A result that only reports its wins is marketing. A good part of this work's value is that it reports where it does *not* win.

Under extreme loading — payloads above 95% of rated capacity on the maximum-grade segments — the energy gains shrink. The reason is deliberate: in that regime the model prioritizes protecting the traction system over saving energy. When protecting the engine and saving energy come into conflict, it chooses the engine. The result is a cycle-time penalty above the reported average and a smaller saving.

That is not a flaw: it is the model's judgment working. A damaged asset at a high-altitude operation — where a major component change idles a several-hundred-tonne truck for days — costs far more than a slow cycle. The hierarchy is correctly placed: safety and the asset first, energy second, and never at the expense of the first two.

For a buyer, this is the due-diligence question that separates a serious optimizer from a naive one: *what does your system do when energy, production and asset health come into conflict?* A system that cannot answer that with an explicit hierarchy is not ready to touch the dispatch of a real fleet.

08

THE CONTEXT HAS ALREADY REACHED THE ANDES

None of this is theoretical for Chilean copper. The infrastructure this digital twin operates on — haulage electrification — is already on site, and the pressure that makes it urgent already has dates on the regulatory calendar.

What is already operating. In 2025, Collahuasi commissioned at its Rosario pit the first operational trolley assist in Chile and South America, above 4,000 meters, powered by renewable electricity: on the electrified segment diesel falls by about 98% and speed rises from 11 to 25 km/h.[10] BHP filed the environmental study to electrify the Escondida Norte pit with trolley — in the Antofagasta Region — targeting the elimination of around 350 million liters of diesel per year across the Escondida and Spence operations.[11] And Codelco announced it will trial Caterpillar's dynamic-charging system on moving trucks at Radomiro Tomic from 2026.[12] Three of the country's largest operations, moving the same piece.

What turns it from good practice into obligation. Chile's Energy Efficiency Law 21.305 obliges large consumers — mining among them — to operate an Energy Management System and report their consumption and energy intensity to the Ministry of Energy, under SEC enforcement.[13] In parallel, CMF General Rule 461 requires listed companies — several miners included — to disclose their Scope 1 and 2 emissions in the annual report, TCFD-aligned, with the full standard landing in 2026.[14] Haulage energy has stopped being an internal metric: it is a number that gets reported, audited and compared.

> **KEY INSIGHT —** For Antofagasta Minerals, Scope 2 is already solved: 100% renewable contracts since 2022. What remains standing is Scope 1: 1.23 million tonnes of CO_2 equivalent in 2024, dominated by haulage diesel. That is the frontier, and Antofagasta Minerals' target of halving those emissions by 2035 has to bite into Scope 1.

The Antofagasta Minerals case makes it sharp: with electricity already decarbonized, haulage diesel is what separates the company from its target of halving Scope 1 and 2 emissions by 2035.[15] Every point of energy efficiency in haulage now counts twice: in operating cost and in the emissions report that is now mandatory.

One objection worth neutralizing up front. If you are reading this, your fleet most likely already runs on an FMS — Komatsu DISPATCH, Caterpillar MineStar or equivalent — chosen years ago. The digital twin we describe does not replace that decision: it operates *on top of* it. It takes the telemetry your system already produces and returns recommendations that enter its dispatch logic. The question is not "do I change my FMS?", but "do I add the layer it does not have today?".

---

[10] Reported elevations for Collahuasi vary by source (≈4,000-4,600 m across the deposit); the Rosario pit, where the trolley operates, sits at the high end of that range.

[11] The ~350 million liters/year of diesel and the ~200-truck fleet (across Escondida and Spence) come from BHP's media release announcing the trolley project; the Environmental Impact Statement filed with Chile's SEIA considers an investment on the order of US$250 million. (BHP's current Escondida haul fleet is reported as 160+ trucks; the ~200 figure spans both operations.)

[12] One-year pilot with Caterpillar 798 trucks on an electrified segment under motion; projected reduction of 60-70% per truck. It is a validation trial, not a fleet-electrification commitment.

[13] Law 21.305 (2021) obliges Consumers with Energy Management Capability — above 50 teracalories a year, a threshold large mines exceed — to implement an Energy Management System covering at least 80% of consumption, appoint an energy manager and file annual declarations.

[14] NCG 461 (2021) embeds ESG disclosure in the annual report of CMF-registered issuers, aligned with TCFD and SASB; Scope 1 and 2 emissions are mandatory and the full (ISSB-aligned) standard applies from fiscal year 2026, whose reports are published in 2027. The rule reports at consolidated corporate level, not per asset.

[15] Antofagasta Minerals: carbon neutrality by 2050, interim target of −50% Scope 1 and 2 by 2035 (2020 base); 100% renewable electricity contracts since April 2022 (Scope 2), with Scope 1 — 1.23 Mt CO_2e in 2024 — dominated by diesel.

09

FROM SIMULATION TO THE MINE: WHAT TO DEMAND

The work is explicit that taking this to a real operation demands three things. We list them, but the list is the easy part; what separates someone who has done it from someone generating content is knowing where the real friction sits.

Integration with your FMS/AHS — and here is the most underestimated obstacle. It is not technical. It is getting your FMS vendor's team to open the dispatch API far enough to receive external recommendations. A twin that decides is worthless if the decision has no way into the system that dispatches; that negotiation — commercial and contractual more than engineering — is usually the project's critical path, and it almost never appears in the proposal.

Safety validation as scope, not as a permit filed afterwards. Any recommendation that modulates the speed of a several-hundred-tonne autonomous truck crosses a safety threshold. The AHS envelope and the operational constraints are not negotiable; the optimizer works *inside* them. That is designed and validated from day one, not processed at the end.

Calibration against your mine, not a catalogue. The model is physical, but its parameters are local: the rolling resistance of *your* roads, the profiles of *your* ramps, the thermal behavior of *your* fleet at *your* altitude. And calibration drifts — a change in the running surface or the mine plan moves it. The twin that works is the one that stays calibrated, not the one delivered calibrated once.

> **KEY INSIGHT —** The most underestimated obstacle is not technical: it is getting your FMS vendor to open the dispatch API far enough to receive external recommendations. That negotiation, not the model, is usually the critical path.

That is why NTT DATA's angle here is not the *what* — the what is defined by the model, and the industry will converge on it. It is the *how*: how it integrates with a mine's real systems landscape, how it is validated without compromising safety, how it stays calibrated, and how the hierarchy of objectives is governed when energy, production and the asset compete. That is implementation engineering, and it is where a promising pilot becomes — or fails to become — an operation you can defend.

> *Haulage is the mine's biggest energy line, and the decision that moves it most is made by a system that does not look at it. The digital twin that matters is not the one that shows the problem: it is the one that decides — with energy inside, within the safety envelope, protecting the asset when everything else competes. In simulation it already performs. Taking it to the ramp is implementation engineering, and that is the work.*

10

KEY INSIGHTS

1 Haulage is the mine's biggest energy lever, and the decision that moves it most — the speed profile, cycle by cycle — is made by a system that cannot see energy. Closing that gap is not another dashboard: it is putting energy inside the decision.

2 The digital twin that matters is not the one that shows. It is the one that decides in closed loop and hands the play back to dispatch.

3 On ramps, energy is non-linear in payload, grade and environment. Productivity-driven dispatch over-prioritizes throughput exactly where the energy penalty spikes — not through error, but by optimizing a single variable.

4 In simulation, the twin delivered 6.4% less energy per tonne while conceding just 1.8% of cycle time, and cut cycle variability by almost 5%. Energy and production stopped competing.

5 The model's honesty is part of its value: under extreme loading it chooses to protect the drivetrain over saving energy. These results are not yet validated in the field — that is what comes next, and it is the conversation a serious project has from day one.

6 You most likely already run an FMS chosen years ago. The twin does not replace it: it operates on top of it. And the most underestimated obstacle to connecting it is not technical — it is opening the vendor's dispatch API.

11

SOURCES

The digital twin's performance figures — energy, cycle time, variability and thermal events — come from the authors' simulation work and are reported as results of calibrated physics simulation, not field operation. Industry-context figures are supported by the public sources below.

- Authors' source work: *Closed-Loop Energy-Aware Digital Twin for Trolley-Assisted CAEX Haulage / Beyond Productivity: Energy-Optimized Digital Twins for Surface Mine Truck Haulage at High Altitude* — Priscila Alves and Víctor Baeza, NTT DATA Chile, 2026.
- Loading + haulage ≈ 75% of open-pit extraction-process energy in Chile — Energía en Minería, Ministry of Energy — energiaenmineria.cl.
- Haulage share of open-pit energy and emissions (>30% of energy, >50% of Scope 1) — *Scientific Reports* (2025) — PMC12216276.
- Chile's Energy Efficiency Law 21.305 (2021): mandatory Energy Management System and reporting for large consumers (mining included), enforced by the SEC — Ministry of Energy — energia.gob.cl/panel/ley-21305.
- CMF General Rule 461 (2021): mandatory TCFD-aligned Scope 1 and 2 disclosure in the annual report; full standard from 2026 — cmfchile.cl.
- Antofagasta Minerals: −50% Scope 1 and 2 target by 2035 (2020 base), 100% renewable electricity contracts since 2022 — antofagasta.co.uk/sustainability/climate-change; 2024 Scope 1 ≈ 1.23 Mt CO_2e from the Annual Report 2024 KPIs — antofagasta.co.uk/investors/annual-report-2024/kpis.
- Collahuasi: South America's first trolley assist at the Rosario pit, above 4,000 m, −98% diesel on the segment, speed 11→25 km/h — *International Mining*, July 2025 — im-mining.com.
- BHP/Escondida (Antofagasta Region): Environmental Impact Statement filed for trolley assist, ~US$250 million investment — *International Mining*, July 2024 — im-mining.com. The ~350 million liters/year of diesel avoided and ~200-truck fleet (across Escondida and Spence) are from BHP's own media release — bhp.com.
- Codelco: Caterpillar Dynamic Energy Transfer (dynamic charging) pilot at Radomiro Tomic, starting 2026 — *International Mining*, October 2025 — im-mining.com.
- Machine-learning techniques for mining energy optimization (≈15% energy in digital-twin deployments; up to 20% from reinforcement-learning ventilation control) — *Frontiers in Energy Research* (2025) — frontiersin.org.
- Copper Scope 1 reductions still lagging; 87% of copper comes from open pits — S&P Global Market Intelligence (2024) — spglobal.com.

NTT DATA · Natural Resources Practice · 2026 · biztalksnttdata.com

For more on this topic, contact: ***Priscila Alves****, Natural Resource Manager, NTT DATA* · priscila.alvescastromartins@emeal.nttdata.com.