



AURUS MINING

The Living Asset

Digital twins for mineral systems and infrastructure decisions

WP11 | DESIGN

MINING | INFRASTRUCTURE | ENGINEERING | ENVIRONMENT



OUR POSITION

A digital twin only earns the name when it operates as a governed decision system: a persistent, synchronized link between a specific physical instance and its digital representation, with controlled configuration, explicit uncertainty and accountable operational action. Treating “twin” as a software label hides the real work in data architecture, model risk

EVIDENCE FIRST | DECISIONS MADE EXPLICIT | DELIVERY CONDITIONS STATED

Contents

S	Executive summary The paper in one decision frame	4
M	Method and boundaries Audience, method and limitations	6
01	A twin is a decision system Use standards-grounded definitions to separate a decision system from a software label, then anchor scope in the decisions that must be taken and audited.	7
02	Asset identity and configuration A twin only stays synchronized if the physical asset is uniquely identified and its configuration is controlled across life-cycle changes.	11
03	Data architecture Data architecture is where synchronization, interoperability and information exchange become testable design artifacts, not aspirations.	15
04	Models and uncertainty A twin becomes operational only when its models are matched to decision needs and when uncertainty is explicit, traceable and governed.	19
05	Mine and plant applications Use mining-specific evidence to define where twins can support decisions today, and where barriers require staged authority and careful measurement.	23
06	Corridor and infrastructure applications Extend the decision-system framing from the pit and plant into corridors and shared infrastructure, where interoperability, monitoring and cross-stakeholder governance dominate.	27
07	Governance and cyber risk A twin concentrates context and authority. Governance and cyber controls must be designed as operational safeguards, not appended as compliance paperwork.	31
08	The twin readiness gate A readiness gate prevents premature operational authority by testing whether data, interoperability, models and governance can sustain synchronization and audit under change.	35
R	Decision tools and references Checklist, evidence ledger, glossary and sources	39

Executive summary

A digital twin is not a screen, a simulation file, or an IoT dashboard. It is a virtual representation of real-world entities and processes that stays synchronized at a specified frequency and fidelity, and that synchronization is constitutive, not optional. Standards and industry definitions converge on the same dividing line: a one-off model run is not a twin because it does not preserve a persistent data linkage to a specific physical instance. Decision value comes when the synchronized representation is used to choose and to act, with those actions traceable back to the data and assumptions that produced them.

Sources: WP11-01, WP11-05

Mining has a clear incentive to move from isolated digital initiatives to operational decision systems, but published evidence still describes a gap between projected value and consistent adoption. A widely cited industry estimate projected more than US\$425 billion of value at stake over the ten years to 2025, and more than US\$320 billion as direct industry value, but those figures are a 2017 projection and must be treated as such. The same source framed digitalization as a response to structural productivity pressure from declining head grades, deeper deposits and rising input costs. The practical question is not whether value exists, but which decisions your organization can govern end to end.

Sources: WP11-06, WP11-07, WP11-12, WP11-26

Published mining reviews show that digital-twin concepts span the full value chain, from exploration through drilling, blasting, loading, hauling, processing and environmental issues. They also report why many processes still rely on human oversight: remote operations, geological variability, high investment costs and a skills gap. Recurring barriers are consistent across the literature and include data quality, availability and latency, plus interoperability across heterogeneous OT and IT systems. These barriers point to a design priority: treat asset identity, configuration and interoperability as first-class engineering problems, not as integration afterthoughts.

Sources: WP11-14, WP11-16

This paper frames a twin as a governed decision system that links models, sensors, configuration, uncertainty and accountable action. It draws on standards terminology, an ISO reference-architecture lens from manufacturing that is explicitly generic, and mining interoperability guidance that positions interoperability as central to automation and integration outcomes. It also uses monitoring expectations in tailings management as a concrete example where instrumentation, anomaly alerting and life-cycle surveillance are decision-critical. The closing chapter defines a twin readiness gate as a data-readiness and governance test, not as a delivery method or a software selection exercise.

Sources: WP11-03, WP11-04, WP11-17, WP11-23

At a glance

Six evidence markers establish the scale, threshold or decision condition carried into the chapters that follow.

Definition

TWIN REQUIRES SYNCHRONIZATION AT SPECIFIED FREQUENCY AND FIDELITY

Source: WP11-01

Distinction

PERSISTENT LINKAGE TO A SPECIFIC PHYSICAL INSTANCE SEPARATES TWIN FROM ONE-OFF模拟

Source: WP11-05

2017 projection

VALUE AT STAKE > US\$425BN OVER 10 YEARS TO 2025 (NOT REALIZED OUTCOMES)

Source: WP11-06

2017 projection

INDUSTRY VALUE > US\$320BN SPLIT US\$190BN MINING AND US\$130BN METALS

Source: WP11-07

Interoperability

INDUSTRY CONSENSUS BUILT FROM 17 MINING COMPANIES ON SIX CONTINENTS

Source: WP11-18

Monitoring

GISTM DESCRIBES 6 TOPIC AREAS, 15 PRINCIPLES, 77 AUDITABLE REQUIREMENTS

Source: WP11-22

Method and boundaries

This paper is a bounded synthesis of registered public evidence. Source identifiers remain visible so that each quantitative or framework statement can be traced to its dossier row.

INTENDED READERS

- CFO
- COO
- Asset Management leaders (mining and processing)

READING METHOD

- Read each chapter opener as a decision frame.
- Use the three section exhibits as working review instruments.
- Return to the evidence ledger before reusing any number or requirement.

BOUNDARIES

- WEF value-at-stake figures are a 2017 forward projection to 2025 and are cited only as that projection, not as realized outcomes. [WP11-12, WP11-06]
- ISO/IEC 30173:2023 and ISO 23247 texts are paywalled; citations rely on the ISO catalogue record and a NIST analysis record, without reproducing clause text. [WP11-03, WP11-04]
- The systematic review statistic (68 studies, 2015 to 2025) is taken from indexed search record and published metadata; the full publisher page capture was blocked during archival fetch per dossier note. [WP11-13]
- The evidence base does not provide audited realized ROI point figures for digital twins in mining; the paper avoids inventing such figures and focuses on decision-system controls and readiness criteria derived from standards and reviews. [WP11-16, WP11-12]

PUBLICATION DISCIPLINE

- No client identity or company-age claim is published.
- No Aurus delivery result is inferred from public guidance.
- Dated forecasts retain their institution and vintage.

01

FRAMING

A twin is a decision system

Use standards-grounded definitions to separate a decision system from a software label, then anchor scope in the decisions that must be taken and audited.

Sync

SYNCHRONIZATION MECHANISM IS CONSTITUTIVE | WP11-02

Instance

TWIN LINKS TO A SPECIFIC PHYSICAL INSTANCE | WP11-05

STEPS scenario

COPPER DEMAND +30% BY 2040 (CONTEXT ONLY) | WP11-24

1.1 1.1 Define the boundary: representation plus synchronization

The most useful starting discipline is definitional. A digital twin is a virtual representation of real-world entities and processes that is synchronized at a specified frequency and fidelity. In practice, that forces a design conversation about what “specified” means in your operation: which variables, at what cadence, and at what error tolerance. It also prevents category drift where any model or historian trend is rebranded as a twin. When a team uses the term “twin,” insist on naming the physical instance, naming the synchronization mechanism, and stating the target frequency and fidelity. Without those elements, the system may still be valuable, but it is not a twin in the standards sense.

WP11-01, WP11-02

ISO terminology makes the separation explicit by distinguishing a digital twin from simulation, cyber-physical systems, asset administration shells and IoT. The defining property is persistent, synchronized data linkage to a specific physical instance, not a one-off run. That distinction matters for decisions. A one-off simulation can support design studies, but it cannot support accountable operational action unless it stays tied to the evolving state of the asset and its configuration. A twin therefore becomes a decision system when it couples a persistent linkage with a decision loop: observe, interpret, decide, act, and record what changed in both the physical asset and its representation.

WP11-05, WP11-03

DECISION INSTRUMENT

Decision test: is it a twin or a model?

Use this as a gate before funding or naming any initiative as a digital twin.

TEST	EVIDENCE READING	DECISION RESPONSE
Physical instance	Named asset or facility instance with clear boundaries; not a generic class model.	If no named instance, treat as simulation or reference model, not a twin.
Synchronization mechanism	Defined data linkage between physical and virtual; includes cadence and update responsibilities.	If linkage is ad hoc or manual, classify as analytics pipeline until automated controls exist.
Specified frequency and fidelity	Target update rate and accuracy for the decisions in scope.	If frequency and fidelity are undefined, stop and restate the decision use case.
Decision loop and audit	Recorded decisions and actions traceable to inputs and assumptions.	If actions are not traceable, treat as visualization only and do not grant operational authority.

Sources: WP11-01, WP11-05

1.2 1.2 Start from decision pressure, not tooling

Mining decision pressure is amplified by demand and cost context, but context must be cited carefully. One cleared scenario statement projects copper demand rising by 30 percent by 2040 under a stated scenario, and separate commodity forecasts show how price expectations change year to year. These signals do not justify a particular technology choice, but they do explain why decision cycles tighten: capital allocation, maintenance windows, throughput targets and risk tolerances are reviewed more often and with higher scrutiny. A twin design should therefore begin with a decision inventory, not with a platform shortlist. Define which decisions are recurrent, material and time constrained, then ask what state information and model support those decisions require.

WP11-24, WP11-25

A decade-old industry projection estimated more than US\$425 billion of value at stake over the ten years to 2025 from digital transformation, described as 3 to 4 percent of industry revenue. The same 2017 work framed the opportunity as a response to declining head grades, deeper deposits and rising input costs. These figures are projections with a fixed vintage. Use them as a motivation to examine decision quality, not as proof that any given twin will pay back. A practical way to respect the evidence is to translate “value at stake” into accountable decisions: which decisions can reduce injuries, prevent instability, or avoid unplanned downtime, and what would be required to measure that in your context.

WP11-06, WP11-12, WP11-26

DECISION INSTRUMENT

Decision inventory worksheet for twin scoping

Convert market and cost context into a bounded set of decisions with measurable acceptance criteria.

TEST	EVIDENCE READING	DECISION RESPONSE
Decision name	One sentence decision, owner, and decision cadence.	Reject any use case that cannot name an accountable owner and cadence.
Materiality	Link to a safety, production, cost, or compliance exposure that is meaningful to leadership.	Prioritize decisions with explicit consequence thresholds.
Information need	State variables, configuration state, and context needed to decide.	If the information list is unbounded, split the decision into smaller decisions.
Verification	How the decision will be evaluated post action.	If verification is undefined, treat as exploratory analytics, not an operational twin.

Sources: WP11-06, WP11-25

1.3 1.3 Frame the twin as a controlled life-cycle system

ISO terminology positions the twin in a broader system context with life-cycle processes and stakeholders. That orientation is practical for mining because assets live through design, construction, commissioning, operations, modification, closure and legacy stewardship. A decision system that only works during one phase will fail at handover unless identity, configuration and data contracts survive the transition. The definition also implies that multiple stakeholders consume and affect the twin, which creates a governance burden. When the twin is treated as an engineering system, it inherits change control, testing and acceptance requirements similar to other operational systems. When it is treated as a label for a dashboard, those controls are often skipped.

WP11-03

A second standards lens is the ISO 23247 series, analyzed by a national metrology institute as a generic framework that can be specialized to discrete, batch or continuous processes. Mining and minerals processing often combine continuous operations with batch events and episodic maintenance, so a layered architecture that separates representation, information exchange and system concerns can reduce ambiguity. The main decision implication is modularity: if layers and interfaces are specified, you can change sensors, models or consumers without breaking the whole system. This is not a claim of suitability to any mine. It is a disciplined way to ask whether your design can evolve while preserving synchronization and auditability.

WP11-04

DECISION INSTRUMENT

Life-cycle control map for a decision twin

Assign minimum controls per life-cycle phase so the twin remains a decision system, not a one-time build.

TEST	EVIDENCE READING	DECISION RESPONSE
Design and build	Define stakeholders, decision scope, and acceptance tests for frequency and fidelity.	Do not proceed to implementation without an agreed acceptance test set.
Commissioning	Prove synchronization mechanism and establish baseline configuration.	Withhold operational authority until baseline is signed off.
Operate and modify	Run change control for models, sensors, and configuration; retain audit logs.	Treat uncontrolled changes as incidents and roll back.
Handover and closure	Preserve identity, configuration history, and data contracts for stewardship.	Require a documented decommission plan for data feeds and access.

Sources: WP11-03, WP11-04



02

CONTROL

Asset identity and configuration

A twin only stays synchronized if the physical asset is uniquely identified and its configuration is controlled across life-cycle changes.

Stakeholders

STANDARDS RECOGNIZE MULTIPLE STAKEHOLDERS AND LIFE-CYCLE PROCESSES | WP11-03

Barrier

INTEGRATION COST AND INTEROPERABILITY RECUR AS ADOPTION BARRIERS | WP11-16

2017 projection

CONNECTED WORKER VALUE AT STAKE
~US\$85BN (INITIATIVE TABLE) |
WP11-10

2.1 2.1 Establish asset identity before instrumentation scale

Persistent linkage to a specific physical instance is the twin’s defining property, so identity design is not optional. In mining this means more than a fixed asset register. You need identity for mobile equipment, fixed plant, electrical systems, civil structures and geotechnical elements, including tailings facilities where life-cycle surveillance is expected. ISO terminology emphasizes stakeholders and context, which is a cue to design identity as a shared contract across operations, maintenance, engineering, and risk functions. If each function maintains its own identifiers, synchronization degenerates into repeated mapping work and error. Start by defining the asset boundary for each decision use case, then define the minimal identity attributes that must remain stable through modifications and replacements.

WP11-05, WP11-03, WP11-23

Literature reviews note that heterogeneous OT and IT systems and interoperability limitations are recurring barriers, alongside integration cost. Identity is where those barriers first appear because each system often encodes asset hierarchy differently. The goal is not a universal hierarchy, but a governed mapping that is stable and versioned. The Digital Twin Consortium definition also points to the need to represent past and present and to simulate predicted futures. That requires that identity persists across time so historical data, events and model outputs can be compared without ambiguity. A practical decision rule is that no model output, alert or recommendation enters an operational workflow unless it is bound to a versioned asset identity and configuration state.

WP11-16, WP11-02

DECISION INSTRUMENT

Asset identity minimum viable contract

A decision-oriented identity set that supports synchronization and audit without overfitting early design.

TEST	EVIDENCE READING	DECISION RESPONSE
Unique identifier	Stable ID for the physical instance; not re-used after retirement.	Block data ingestion that lacks a stable asset ID.
Boundary definition	Spatial and functional boundary for the asset instance in the decision scope.	If boundary is unclear, treat outputs as advisory only.
Hierarchy link	Parent-child relations needed for aggregation and roll-up decisions.	Require hierarchy validation before reporting KPIs to leadership.
Time validity	Start and end dates for identity and mapping changes.	Do not merge histories across identity changes without explicit approval.

Sources: WP11-05, WP11-16

2.2 2.2 Configuration is the hidden state of the twin

Synchronization fails when configuration is implicit. A twin must represent measured state and configuration state: what equipment is installed, what firmware and control logic are active, what setpoints are authorized, and what calibration states apply. Standards terminology covers life-cycle processes and stakeholders, which implies that configuration changes originate in multiple places. Without control, the system silently compares sensor values to the wrong model parameters, or routes alerts to the wrong thresholds. The WEF initiative table included “smart sensors,” “remote operations,” and “connected worker” as major value categories in a 2017 projection. Those initiatives all assume that the organization can tell which configuration was active when an event occurred, which is a configuration management requirement before it is a technology requirement.

WP11-03, WP11-10, WP11-12

Mining reviews report data quality, availability and latency as recurring adoption barriers, but configuration is a primary cause of apparent “data quality” problems. A sensor that is correct for one layout may be misleading after a process change. Geological and process variability compound the issue because plant behavior changes with ore characteristics, so teams tune control and operating practices more often. If those changes are not captured as configuration, model error looks like process noise. Treat configuration as a first-class data product with versioning, approvals and audit, and connect it to identity so each time series and model run can be interpreted in its proper context. This is a governance choice that reduces rework later.

WP11-16, WP11-14

DECISION INSTRUMENT

Configuration baseline decision matrix

Decide which configuration items must be controlled to grant the twin operational authority for a use case.

TEST	EVIDENCE READING	DECISION RESPONSE
Configuration item class	Equipment, control logic, calibration, operating envelope, model version.	Select only items that change decision outcomes for the use case.
Authority level	Who can approve changes and who can view pending changes.	Separate approval authority from implementation roles.
Effective time	When the change is active and how it is recorded.	Require effective-time stamping before data is used in models.
Fallback rule	What happens when configuration is unknown or disputed.	Downgrade outputs to advisory and trigger verification workflow.

Sources: WP11-03, WP11-16

2.3 2.3 Connect identity and configuration to value claims with discipline

Industry value projections can mislead if they are treated as a promise rather than a hypothesis. The WEF 2017 work projected more than US\$320 billion of industry value over a decade, split between mining and metals, and listed initiative categories such as remote operations and autonomous operations. Those numbers do not specify which operational decisions were improved, or what measurement method was used to attribute value. That gap is acknowledged in the evidence dossier and must remain explicit. The practical response is to set an internal measurement contract: when a decision twin is proposed, define the decision, the baseline, the measurement window, and the boundary of attribution. Identity and configuration are prerequisites for such measurement because they define what “the asset” was during the period being measured.

WP11-07, WP11-10, WP11-12

Reviews across the mining value chain show that digital-twin systems are discussed from exploration to environmental issues, but they also note high investment costs and a skills gap. Identity and configuration are the lowest-regret investments because they reduce future integration friction and enable staff to reason about system changes. They also create clarity for cooperation across functions, which aligns with an industry outlook that stresses cooperation across industry, governments, technology companies and communities. Even if a full twin is not pursued, a governed identity and configuration layer improves reliability of reporting and analysis. If a twin is pursued, those layers keep synchronization meaningful and keep accountability intact when the system begins influencing operational actions.

WP11-14, WP11-21

DECISION INSTRUMENT

Measurement contract for decision twins

A lightweight contract to prevent value narratives from drifting away from evidence.

TEST	EVIDENCE READING	DECISION RESPONSE
Decision and boundary	Exact decision, asset boundary, and operating conditions included.	Refuse any claim that cannot name boundary and conditions.
Baseline period	Defined baseline configuration state and time window.	Do not compare across configuration regimes without adjustment.
Attribution rule	What portion of outcome is attributed to the decision system versus other changes.	If attribution is ambiguous, report as observational, not causal.
Audit trail	Link outcomes to identity, configuration, and model versions used.	Treat missing links as a control failure and correct before scaling.

Sources: WP11-12, WP11-16

03

FOUNDATION

Data architecture

Data architecture is where synchronization, interoperability and information exchange become testable design artifacts, not aspirations.

Layered view

ISO 23247 PARTITIONS A TWINNING SYSTEM INTO LAYERS AND INFORMATION EXCHANGE | WP11-04

Consensus

GMG INTEROPERABILITY WORK SYNTHESIZED INTERVIEWS AND WORKSHOPS WITH 17 COMPANIES | WP11-18

Priority

INTEROPERABILITY DESCRIBED AS KEY TO SUCCESS IN AUTOMATION AND INTEGRATION | WP11-17

3.1 3.1 Architect for synchronization, not accumulation

A twin’s data architecture is defined by synchronization requirements, not by how much data can be stored. The Digital Twin Consortium description states that digital-twin systems use real-time and historical data to represent past and present and to simulate predicted futures, with synchronization between virtual and real as a constitutive element. That implies at least two data paths: a low-latency path that supports near-term decisions, and a governed history that supports diagnostics, learning and audit. The architecture question is what fidelity is needed for the decisions in scope, and whether that fidelity depends on event-level integrity, time alignment, or contextual metadata such as configuration versions. If the architecture cannot demonstrate time alignment and context binding, the system will drift into a data lake that cannot support accountable action.

WP11-02

ISO terminology emphasizes a digital-twin system context and stakeholders, which should shape your data contracts. In mining operations, stakeholders include control-room operators, reliability engineers, geotechnical teams, and governance functions that need traceable evidence of what was known when a decision was taken. Data architecture therefore must include explicit ownership and access rules, more than pipelines. ISO also positions the digital twin relative to IoT, which helps avoid a common trap: confusing connectivity with decision readiness. Sensors can stream, but without identity, configuration, and validation, streams do not become synchronized state. Design architecture around the minimum data products required to support a decision, and build validation at the point of ingestion so downstream consumers do not reinvent quality rules.

WP11-03, WP11-05

DECISION INSTRUMENT

Synchronization data-path design choices

Make the trade-offs explicit before selecting platforms or middleware.

TEST	EVIDENCE READING	DECISION RESPONSE
Cadence class	Real-time, near-real-time, shift-based, event-based.	Select cadence by decision need, not by sensor capability.
Time alignment rule	Clock source, latency budget, and resampling method.	If time alignment is unprovable, do not automate decisions.
Context binding	How configuration and identity versions are attached to records.	Reject records lacking valid context metadata.
Audit retention	Retention period for raw signals, derived features, and decisions.	Retain sufficient history to reproduce decisions during reviews.

Sources: WP11-01, WP11-02

3.2 Interoperability is a design requirement

Interoperability is not a late integration task; it is a primary design requirement for any decision system that spans equipment, plant, and infrastructure. An industry alignment report describes interoperability as the key to success in automation, digitalization and integration initiatives. It also documents that the consensus view was gathered through interviews and workshops with 17 mining companies on six continents, and summarizes definitions, principles and priorities. Treat that as a signal that interoperability is an operational risk issue, more than an IT preference. When a twin depends on many source systems, an interface failure becomes a decision-quality failure. Specify interface contracts, naming conventions and data semantics early, and align them across OT and IT boundaries so the system remains maintainable under change.

WP11-17, WP11-18

A standards lens helps structure this work. ISO 23247, as analyzed by a national institute, defines a reference architecture and information exchange concerns as part of a layered approach, and it is explicitly generic across process types. While mining is not manufacturing, the architecture concept still helps: represent elements, define how representations are exchanged, and separate layers so one change does not collapse the system. Pair this with mining interoperability consensus to create a practical specification: what data must be exchanged, at what latency, with what semantics, and how errors are handled. The goal is not maximum integration. The goal is predictable, testable information exchange that preserves synchronization properties required by the definition of a twin.

WP11-04, WP11-01, WP11-18

DECISION INSTRUMENT

Interoperability contract for a decision twin

Use as a procurement and engineering control to keep interfaces stable and auditable.

TEST	EVIDENCE READING	DECISION RESPONSE
Semantic agreement	Common meaning for tags, units, coordinate frames, and event codes.	Block integration where semantics are undocumented.
Interface behavior	Latency expectations, retry rules, and error reporting.	Treat silent failure as unacceptable for decision authority.
Versioning	API and schema versions with deprecation policy.	Require backward compatibility or planned cutover windows.
Test harness	Automated tests for data completeness and timing.	No production release without passing interface tests.

Sources: WP11-17, WP11-04

3.3 3.3 Data access and usage must be governed

A liaison agreement between a mining guidelines group and the Digital Twin Consortium signals that data access and usage, cybersecurity and asset management are seen as linked workstreams, not separate programs. That alignment matters because a twin concentrates operational context and can amplify the impact of misuse. If access rules are informal, teams either over-share and create risk, or under-share and block decisions. ISO terminology points to stakeholders and a life-cycle context, which implies that access needs change over time and by role. Governance should define who can see raw signals, who can see derived model outputs, who can approve model changes, and who can authorize an action workflow that affects operations. This is not an abstract policy. It is a set of enforceable controls tied to identity, configuration and interfaces.

WP11-19, WP11-03

The evidence base also cautions that data quality, availability and latency are recurring barriers to digital-twin adoption, alongside integration cost and skills gaps. Governance cannot solve physics, but it can prevent self-inflicted failure modes such as uncontrolled data edits, undocumented transformations and inconsistent definitions across sites. A decision system needs lineage. When an operator asks why a recommendation changed, the system must answer with specific inputs and versions, not with vague references to “the model.” Build lineage into architecture using versioned schemas, immutable raw data retention where appropriate, and explicit ownership of transformations. Make access and usage controls part of readiness criteria, not something addressed after rollout, because retrofitting governance into a live operational system is costly and disruptive.

WP11-16, WP11-14

DECISION INSTRUMENT

Minimum data-governance controls for twin candidates

A practical baseline that links access, lineage, and change control to decision authority.

TEST	EVIDENCE READING	DECISION RESPONSE
Role-based access	Roles defined for viewing, editing, approving, and acting.	Deny action authority to any role without training and audit requirements.
Lineage recording	Transformations recorded from source to model output.	If lineage is missing, mark outputs as non-operational.
Change control	Formal process for schema, tag, and transformation changes.	Treat uncontrolled changes as incidents.
Data-quality rules	Validation rules for completeness, range, and timing.	Quarantine data that fails rules and notify owners.

Sources: WP11-16, WP11-19

04

MODEL RISK

Models and uncertainty

A twin becomes operational only when its models are matched to decision needs and when uncertainty is explicit, traceable and governed.

Scope

DIGITAL-TWIN REVIEWS SPAN EXPLORATION TO ENVIRONMENTAL ISSUES | WP11-14

Replica

PROCESS DIGITAL TWIN DESCRIBED AS DYNAMIC SIMULATION OF ORE PROCESSING | WP11-15

Evidence base

SYSTEMATIC REVIEW EXAMINED 68 STUDIES PUBLISHED 2015 TO 2025 (METADATA) | WP11-13

4.1 4.1 Choose model types by decision class

Mining literature describes digital-twin systems across many domains, which is a reminder that “twin” is not a single model type. For minerals processing, a process digital twin has been described as a digital replica of ore processing for a plant, using dynamic simulation with physical properties and chemical processes at each refining step. That description implies strong coupling between measured variables and model states, and it suggests where model fidelity matters. For other decisions, simpler statistical or rule-based representations may be sufficient. The standards-grounded definition does not demand any particular model, but it does demand synchronization and persistent linkage to the physical instance. The design task is to map decisions to model classes, then to define the synchronization and validation needed to keep those models reliable in operations.

WP11-15, WP11-01

A key practical boundary is between decision support and decision authority. The Digital Twin Consortium description includes simulating predicted futures, which invites optimization and forecasting. Yet mining reviews report that many processes still depend on human oversight due to remote operations, geological variability, high investment costs and a skills gap. That is an operational reality. It suggests that early twins should focus on decision support with explicit uncertainty, and that automation should be introduced only where error consequences are understood and mitigations exist. Define, in writing, which decisions the system can recommend and which it can execute. Then treat that classification as a control, with additional verification steps and tighter data-quality thresholds as you move from advisory outputs toward actions that change physical state.

WP11-02, WP11-14

DECISION INSTRUMENT

Decision to model mapping table

Select the simplest model that meets the decision requirement, then state validation and authority rules.

TEST	EVIDENCE READING	DECISION RESPONSE
Decision class	Monitoring, diagnosis, prediction, optimization, control.	Assign authority level per class before building models.
Model type	Physics-based dynamic simulation, hybrid, statistical, rules.	Prefer simpler types unless fidelity need is proven.
Validation method	Back-testing, holdout periods, event replay, operator review.	No operational use without a defined validation method.
Failure consequence	Safety, environmental, production, cost impacts if wrong.	Set stricter thresholds where consequence is high.

Sources: WP11-15, WP11-14

4.2 4.2 Make uncertainty explicit and actionable

Uncertainty in mining is not a nuisance variable; it is the operating condition. Geological variability and process variability are explicitly noted as reasons for continued human oversight, and as barriers to adoption. If a twin presents point outputs without uncertainty context, it creates false certainty and can degrade decision quality. Instead, define uncertainty statements that match decisions. For monitoring, uncertainty may be a confidence score on anomaly detection. For prediction, it may be a range with assumptions. For optimization, it may be sensitivity to ore characteristics or equipment condition. The Digital Twin Consortium definition points to using historical and real-time data to represent past and present and to simulate predicted futures. Treat those predicted futures as conditional. Require the system to state what inputs and conditions drive the output, and what evidence would change the conclusion.

WP11-14, WP11-02

Standards terminology helps here because it positions the twin relative to simulation. Simulation is often used for what-if analysis with controlled assumptions, while a twin is defined by persistent linkage and synchronization to an instance. When you combine the two, the risk is that simulation assumptions are treated as live truth. Guard against that by separating “state estimation” from “scenario projection” and labeling each output accordingly. Do not let dashboards mix measured state, inferred state, and scenario results without clear labeling. If the organization cannot maintain that clarity, keep the system in decision-support mode and require human review. This is not about slowing progress. It is about preventing a synchronized system from distributing unqualified claims faster than they can be checked.

WP11-05, WP11-01

DECISION INSTRUMENT

Uncertainty declaration template for twin outputs

A standardized statement to attach to any model output that informs an operational decision.

TEST	EVIDENCE READING	DECISION RESPONSE
Output type	Measured, inferred, forecast, scenario.	Label outputs; forbid unlabeled mixing in operational screens.
Uncertainty form	Range, confidence, sensitivity, data completeness score.	Choose a form that supports the decision, more than model convenience.
Key assumptions	Ore properties, operating regime, configuration state, sensor health.	List assumptions; if unknown, downgrade authority.
Change triggers	What evidence would force re-estimation or re-validation.	Automate triggers where possible and route to owners.

Sources: WP11-05, WP11-14

4.3 4.3 Validate models as part of the synchronization mechanism

Synchronization extends beyond a data plumbing problem. It is also a model validity problem. If the system uses measured data to update a representation of the asset, then model drift becomes drift in the twin itself. Reviews cite data latency and availability as barriers, but they also cite skills gaps. That combination often leads to weak validation, where models are built but not continuously checked against changing conditions. A disciplined approach is to define validation as a life-cycle process with owners and schedules, consistent with standards terminology that covers life-cycle processes and stakeholders. Define what “good enough” means for each decision use case and track it. When validation fails, the decision system must degrade gracefully, for example by flagging outputs as advisory or by reverting to simpler rules that are known to be safe under uncertainty.

WP11-16, WP11-03

Evidence on the research base can help calibrate expectations. One systematic review metadata record states it examined 68 primary studies published from 2015 to 2025 on AI-driven digital twins in mining operations, analyzing trends, methods and domains. That breadth indicates active experimentation, but it does not provide a single operational blueprint, and the evidence dossier notes access limitations for archiving the full paper. Use this as a prompt to ask for validation evidence, not as a reason to assume maturity. When considering any model technique, ask what data sources it requires, how it handles missingness and latency, and how it will be monitored in production. In a decision system, ongoing validation is part of synchronization, because it maintains alignment between representation and reality over time.

WP11-13, WP11-16

DECISION INSTRUMENT

Model validation gate for operational use

A gate that must pass before any twin output is allowed to influence operational actions.

TEST	EVIDENCE READING	DECISION RESPONSE
Data sufficiency	Availability, latency, and quality meet minimum thresholds for the decision cadence.	If thresholds are not met, restrict to post hoc analysis.
Performance evidence	Validation results tied to asset identity and configuration regimes.	Reject “average” performance claims that ignore regime shifts.
Monitoring plan	Drift detection, alerting, and owner response times.	No deployment without an assigned monitoring owner.
Fallback behavior	Defined safe state when model is invalid or data is missing.	Require tested fallback for any high-consequence decision.

Sources: WP11-16, WP11-13

05

OPERATIONS

Mine and plant applications

Use mining-specific evidence to define where twins can support decisions today, and where barriers require staged authority and careful measurement.

2017 projection

REMOTE OPERATIONS VALUE AT STAKE
~US\$84BN (INITIATIVE TABLE) |
WP11-10

2017 projection

AUTONOMOUS OPERATIONS VALUE AT
STAKE ~US\$56BN (INITIATIVE TABLE) |
WP11-10

Barrier set

CAPITAL COST, DATA QUALITY, INTER-
OPERABILITY, VARIABILITY, SKILLS GAP
| WP11-16

5.1 5.1 Align use cases to the mining value chain

A mining review describes digital-twin systems spanning exploration, drilling, blasting, loading, hauling, mineral processing and environmental issues. This breadth is useful, but it can also dilute focus if teams pursue too many thin pilots. A better approach is to select a small set of decision loops where synchronization can be maintained and where actions are clear. In mine operations, candidates often center on equipment health and dispatch decisions. In plant operations, candidates often center on stability, throughput and recovery decisions. The evidence base also reports that many processes still rely on human oversight due to remote operations and variability, which suggests starting with decision support and then tightening the loop as measurement and governance mature. In every case, define the physical instance, the synchronization cadence, and the action path before building screens.

WP11-14

Industry outlook commentary also frames exploration’s future as data-first, suggesting that the starting point for future discoveries could be data, and that those prioritizing digitization may be positioned for AI-assisted discovery. That statement is not a twin claim, but it reinforces a design theme: treat data as a first-class asset and align it across functions. For mine and plant twins, that means linking planning data, operations data, maintenance data and laboratory data through consistent identity and semantics. It also means setting clear boundaries between data that supports learning and data that supports action. If you cannot specify what actions will change based on an output, you are building a research environment, not a decision twin. Both can be valuable, but they need different controls and expectations.

WP11-21, WP11-03

DECISION INSTRUMENT

Use case triage: mine and plant decision loops

A triage tool that forces each use case to specify synchronization, action, and verification.

TEST	EVIDENCE READING	DECISION RESPONSE
Decision loop	Example loops: dispatch adjustment, shutdown deferral, setpoint change, maintenance scheduling.	Select loops with clear owners and repeat cadence.
Required synchronization	Variables and update rates needed to avoid stale decisions.	If update rate cannot be met, redesign the decision.
Action pathway	Manual, assisted, or automated action and required approvals.	Start with assisted action where consequences are high.
Verification plan	How outcomes will be measured and audited post action.	Do not scale without a verification plan tied to identity and configuration.

Sources: WP11-01, WP11-14

5.2 Remote, connected, and autonomous operations as decision-system patterns

A 2017 industry projection table assigned large value at stake categories to connected worker, remote operations and autonomous operations. These categories are best read as decision-system patterns rather than as product categories. Connected worker initiatives change how field observations and work execution feed back into operational decisions. Remote operations initiatives change where decisions are made and how state is visualized and controlled. Autonomous operations initiatives change which decisions are executed by machines and under what constraints. The same source projected safety impacts, but those are also projections with 2017 vintage and should not be treated as realized outcomes. For a twin, the practical implication is that each pattern increases the need for synchronization, configuration control and audit. As decision latency decreases, tolerance for missing context decreases even faster.

WP11-10, WP11-12, WP11-09

Autonomous operations projections include a claim of additional value and a split of value accruing to mining, plus projected safety impacts. Treat these as directional motivation, not as guarantees. The design work is to identify which decisions can be constrained enough to automate safely and to define how the twin represents constraints. For example, a dispatch decision might be constrained by geotechnical exclusions, equipment health, and haul-road conditions. If those constraints are not represented, automation increases risk. Mining reviews cite interoperability and data latency as barriers, which are precisely the failure modes that can compromise autonomy. The decision recommendation is staged authority: start with monitoring and advisory outputs, progress to supervised automation where constraints are machine-readable, and only then consider higher autonomy, always with explicit fallback behavior.

WP11-11, WP11-16

DECISION INSTRUMENT

Authority ladder for mine and plant twins

A controlled progression from insight to action with explicit prerequisites at each step.

TEST	EVIDENCE READING	DECISION RESPONSE
Level 0: Observe	Synchronized state view and anomaly alerts only.	Approve when data quality and identity are sufficient for monitoring.
Level 1: Advise	Recommendations with uncertainty statements and operator confirmation.	Approve when validation and audit trails exist.
Level 2: Assist	System executes bounded actions with human approval and logging.	Approve when constraints and rollback are tested.
Level 3: Act	Automated execution within defined envelopes and governance oversight.	Approve only for decisions with proven stability and low consequence failure modes.

Sources: WP11-02, WP11-16

5.3 5.3 Process twins in the plant: tie simulation to operations carefully

A minerals processing description of a process digital twin emphasizes dynamic simulation using physical properties and chemical processes at each refining step. That sets a high bar for data quality, calibration and configuration capture because small sensor biases or unrecorded operating changes can propagate into large output errors. Plant applications therefore benefit from explicit separation of purposes: training and scenario analysis versus live decision support. ISO terminology distinguishes twins from simulation through persistent linkage to a specific instance. Use that distinction as a control: if a model is not synchronized with live data and configuration, call it simulation and use it under simulation governance. If it is synchronized, then require operational validation and uncertainty declaration before it is used to change setpoints or operating envelopes. This preserves trust and prevents the twin label from masking model risk.

WP11-15, WP11-05

Literature reviews report that high investment cost and skills gaps are barriers. In a plant context, these often appear as partial implementations where some unit operations are modeled and others are treated as fixed transfers, creating fragile end-to-end behavior. A layered architecture lens, such as a reference architecture that partitions representation and information exchange, helps teams modularize the plant twin so that scope can expand without rewriting the whole system. Combine that with interoperability principles to manage heterogeneous control systems and laboratory information. The decision system focus remains the same: define which plant decisions are in scope, define required cadence, bind every output to configuration state, and ensure a fallback mode when data or models fail. Without those controls, a process twin becomes an expensive visualization with unclear authority.

WP11-04, WP11-16, WP11-17

DECISION INSTRUMENT

Plant twin scope control: unit operation readiness table

Decide which unit operations are ready to enter an operational decision loop.

TEST	EVIDENCE READING	DECISION RESPONSE
Unit operation	Grinding, flotation, thickening, tailings handling, utilities.	Select only units with sufficient sensors and controlled configuration.
Model fidelity need	Mass balance only, dynamic simulation, chemistry-aware simulation.	Match fidelity to the decision; avoid over-modeling early.
Data dependencies	Sensors, lab assays, control system tags, maintenance states.	If dependencies are unstable, keep the unit in advisory mode.
Operational action	Setpoint change, alarms, maintenance trigger, feed blending change.	Grant action authority only when validation and uncertainty controls are in place.

Sources: WP11-15, WP11-16

06

SYSTEMS

Corridor and infrastructure applications

Extend the decision-system framing from the pit and plant into corridors and shared infrastructure, where interoperability, monitoring and cross-stakeholder governance dominate.

GISTM structure

6 TOPIC AREAS, 15 PRINCIPLES, 77
AUDITABLE REQUIREMENTS | WP11-22

Monitoring

GISTM DRIVES REAL-TIME INSTRUMENTATION AND AUTOMATIC ANOMALY ALERTS | WP11-23

Interoperability

GMG NETWORK SPANS COMPANIES, OEMS, REGULATORS AND ASSOCIATIONS | WP11-17

6.1 6.1 Infrastructure twins are multi-stakeholder by default

Corridors and infrastructure decisions involve more stakeholders than most single-asset decisions. A mining interoperability body describes itself as a network spanning mining companies, OEMs, organizations, academics, consultants, regulators and industry associations. That breadth matters for any corridor-level twin concept because asset ownership, data access and decision rights are often shared or layered. ISO terminology emphasizes stakeholders and system context, which aligns with this reality. The practical implication is that corridor twins require explicit governance of data access and usage from the start, not after technical integration. The system must define which parties can publish data, which can consume it, and which can initiate actions or work orders. If these controls are not clear, a corridor twin becomes a contested reporting environment rather than a decision system.

WP11-17, WP11-03

The same interoperability work describes interoperability as key to success in automation, digitalization and integration initiatives. Corridors amplify interoperability problems because they aggregate fleets, power systems, comms networks, roads, rail, ports, water and tailings infrastructure into a single decision landscape. The twin framing still applies: a persistent, synchronized representation of specific physical instances, updated at defined cadence and fidelity. What changes is the scale of identity and configuration management, and the need to partition the architecture so each subsystem can evolve. A layered reference architecture approach is useful as a structuring tool, even when not adopted verbatim. It encourages teams to separate representation, information exchange, and system concerns so that cross-party integration can focus on stable interfaces and governance rather than on monolithic builds.

WP11-17, WP11-04, WP11-01

DECISION INSTRUMENT

Corridor twin stakeholder and decision-rights map

A map that prevents technical integration from outrunning decision authority and accountability.

TEST	EVIDENCE READING	DECISION RESPONSE
Stakeholder set	Operators, maintainers, owners, regulators, communities, contractors as applicable.	List stakeholders explicitly and assign representation in governance.
Data publishing rights	Who can publish which data products and under what validation rules.	Reject feeds without documented ownership and validation.
Decision rights	Who can authorize actions that affect shared infrastructure.	No automated actions without written decision-rights agreement.
Dispute resolution	Process for resolving conflicting data or interpretations.	Define escalation paths before operational reliance.

Sources: WP11-03, WP11-17

6.2 6.2 Tailings monitoring shows what “decision-grade” looks like

Tailings governance provides a concrete case where monitoring is tied to auditable expectations. An industry standard overview states the Global Industry Standard on Tailings Management comprises six topic areas, 15 principles and 77 auditable requirements, with the goal of zero harm to people and the environment. The same overview notes that implementation drives real-time instrumentation with automatic anomaly alerts as part of integrated monitoring systems, and that upgrading dam monitoring instrumentation is a recognized component of conformance, with enhanced surveillance and continuous monitoring across the facility life cycle. This evidence is not a claim that a tailings monitoring system is a digital twin. It is evidence of decision-grade monitoring expectations: instrumentation, alerting, life-cycle coverage, and auditable requirements. Those are exactly the properties a twin must meet if it will influence high-consequence infrastructure decisions.

WP11-22, WP11-23

If you choose to frame tailings monitoring as part of a broader twin concept, standards definitions keep the boundary clear. A twin requires persistent linkage and synchronization to a specific physical instance, which aligns naturally with a specific facility and its instruments, but the decision system must also include configuration state, such as sensor calibration and structural modifications. The key is to preserve auditability. Since the tailings standard is auditable, any digital decision support must be able to reproduce what the system knew, what it inferred, what alerts were issued, and what actions were taken. That requires architecture choices that preserve raw and derived data, plus governance that controls changes. Mining reviews cite data latency and interoperability as barriers, and those barriers matter intensely for anomaly alerts. Therefore, any “twin” framing for tailings should begin with instrumentation reliability, timing integrity and change control, before advanced modeling ambitions.

WP11-23, WP11-05, WP11-16

DECISION INSTRUMENT

Decision-grade monitoring checklist for infrastructure assets

Use this checklist before treating monitoring outputs as operational decision inputs.

TEST	EVIDENCE READING	DECISION RESPONSE
Instrumentation coverage	Sensors cover the decision-critical failure modes and locations.	If coverage is incomplete, constrain decisions and document blind spots.
Alert integrity	Automatic anomaly alerts with defined thresholds and false-alarm handling.	Do not rely on alerts without documented threshold governance.
Life-cycle continuity	Monitoring maintained through operations, modification, and closure phases.	Require a plan for monitoring upgrades and continuity at handovers.
Audit readiness	Evidence retained to support auditable requirements.	Retain logs and configurations sufficient for audit and investigation.

Sources: WP11-22, WP11-23

6.3 6.3 Corridor value cases require interoperability before optimization

A common mistake in corridor and infrastructure initiatives is to start with optimization narratives before the data exchange is stable. The GMG interoperability alignment work is explicit that interoperability is central to integration outcomes. Use that as a sequencing rule: prove stable information exchange, then add models. ISO 23247 highlights information exchange as a defined part of a twinning framework, which reinforces the need to specify interfaces and exchange semantics. In corridor contexts, start with the decisions that require cross-asset coordination, such as scheduling constraints, capacity bottlenecks, and safety exclusions. Then define the minimum shared data products needed, such as capacity states, availability windows, and constraint statuses, each bound to asset identity and effective times. Without this discipline, optimization becomes fragile because each participant interprets the same terms differently.

WP11-17, WP11-04

Industry outlook messaging that the future is shaped less by competition than by cooperation supports the governance stance needed for corridors. Cooperation is not a slogan. It is a set of shared definitions, shared data contracts, and agreed mechanisms for dispute resolution. That aligns with the liaison between a mining guidelines group and the Digital Twin Consortium, which explicitly connects data access and usage and cybersecurity with digital-twin alignment. In corridor projects, cyber risk and data rights concerns often block progress unless addressed early. Therefore, treat corridor twin design as a negotiated decision system with explicit rights and responsibilities, not as a centralized software build. Architecture should allow each party to maintain their internal systems while exchanging decision-critical information through governed interfaces, so the corridor can coordinate actions without demanding full data pooling.

WP11-21, WP11-19, WP11-17

DECISION INSTRUMENT

Corridor sequencing rule: exchange before optimization

A decision framework to keep corridor programs from outrunning their interoperability foundations.

TEST	EVIDENCE READING	DECISION RESPONSE
Phase 1: Shared definitions	Common terms for capacity, availability, constraints, and events.	Do not build optimization until definitions are signed off.
Phase 2: Stable exchange	Information exchange tested for timing, completeness, and error handling.	Stop scaling if exchange stability is not demonstrated.
Phase 3: Coordinated decisions	Cross-asset decisions executed with clear rights and audit trails.	Grant authority only when rights and logs are in place.
Phase 4: Optimization	Models propose improvements under explicit constraints and uncertainty.	Require sensitivity analysis and fallback behavior before adoption.

Sources: WP11-17, WP11-04

A large industrial facility, possibly a steel mill or refinery, is shown at dusk. The sky is a deep blue, and the facility's lights are glowing, creating a warm, golden light. The structure is complex, with many levels, walkways, and pipes. A long, elevated walkway or conveyor system extends across the middle of the frame. The overall atmosphere is one of industrial scale and activity.

07

ASSURANCE

Governance and cyber risk

A twin concentrates context and authority. Governance and cyber controls must be designed as operational safeguards, not appended as compliance paperwork.

2017 projection

ASSET CYBERSECURITY VALUE AT STAKE ~US\$21BN (INITIATIVE TABLE, PROJECTED) | WP11-10

Alignment

GMG AND DTC LIAISON INCLUDES CYBERSECURITY AND ASSET MANAGEMENT WORKSTREAMS | WP11-19

ISO scope

ISO TERMINOLOGY COVERS STAKEHOLDERS AND LIFE-CYCLE PROCESSES | WP11-03

7.1 7.1 Governance defines decision authority and accountability

When a twin is framed as a decision system, governance becomes the mechanism that grants and limits authority. ISO terminology explicitly includes stakeholders and life-cycle processes, which implies that decisions and responsibilities change over time. Governance therefore must define who owns the asset representation, who owns data quality, who approves model changes, and who can authorize actions based on twin outputs. The Digital Twin Consortium description includes representing past and present and simulating predicted futures. That capability can influence planning, scheduling and risk decisions, but only if decisions are traceable. The governance design should require that every action taken on the basis of a twin output is linked to the versioned inputs and assumptions used. Without this, post-incident reviews devolve into argument about which data and model were active, and trust collapses.

WP11-03, WP11-02

Mining reviews repeatedly cite skills gaps as a barrier, which governance must acknowledge. You cannot govern a system that nobody can operate or validate. Governance should therefore include competency requirements for roles that interpret or act on twin outputs, and it should define escalation paths when outputs conflict with operator judgment. This is consistent with the finding that many processes still rely on human oversight. The goal is not to replace oversight, but to structure it. A controlled decision system allows human intervention to be recorded and learned from, rather than treated as informal override. If governance is clear, the twin can improve decision consistency even when models are uncertain, because the organization can see how decisions were made and can improve the system iteratively.

WP11-16, WP11-14

DECISION INSTRUMENT

Decision authority charter for twin-enabled actions

A charter template that grants authority only where accountability and competence are defined.

TEST	EVIDENCE READING	DECISION RESPONSE
Decision owner	Named role accountable for the decision outcome.	No twin-driven action without an accountable decision owner.
Approval path	Required approvals by decision consequence class.	Define consequence classes and enforce approvals in workflow.
Competency requirements	Training and validation responsibilities for roles using outputs.	Restrict access to action functions until competency is met.
Audit linkage	Required links to data, configuration, and model versions.	Treat missing audit linkage as a control breach.

Sources: WP11-03, WP11-16

7.2 7.2 Cyber risk increases with connectivity and decision authority

A 2017 industry projection table included “asset cybersecurity” with a stated value at stake, and that inclusion is a useful reminder: as digital initiatives connect operational systems, cyber risk becomes an operational risk. The projection does not quantify realized cyber outcomes and should not be treated as such. The practical point is structural. A twin connects data sources, models and action pathways. If compromised, it can spread false state, suppress alarms, or trigger harmful actions. The liaison between a mining guidelines group and the Digital Twin Consortium explicitly connects cybersecurity with digital-twin alignment workstreams, which reinforces that security is part of twin design, not a parallel program. Security architecture must cover identity, access, interface integrity and change control, and it must be tested under realistic failure conditions.

WP11-10, WP11-12, WP11-19

ISO terminology distinguishes a twin from IoT by emphasizing persistent linkage to a specific instance. That same linkage can become an attack surface if identity and access are weak. Cyber controls must therefore be tied to the identity and configuration controls described earlier. For example, if a configuration baseline can be edited without approval, an attacker or an accidental change can shift model parameters and produce plausible but incorrect recommendations. Similarly, if interface semantics are not governed, data poisoning can occur through mislabeling rather than through obvious intrusion. Interoperability initiatives are often pursued to enable integration, but they also expand connectivity. Use the interoperability contract as a security instrument as well: specify authentication, integrity checks, and monitoring for interface failures. Treat silent data failure as a cyber-relevant event when the twin has decision authority.

WP11-05, WP11-17, WP11-16

DECISION INSTRUMENT

Cyber controls tied to twin decision authority

A control set that scales with the authority ladder, not with technology labels.

TEST	EVIDENCE READING	DECISION RESPONSE
Access control	Role-based access for data viewing, model editing, and action initiation.	Increase restrictions as action authority increases.
Interface integrity	Authentication, integrity checks, and monitoring on data exchanges.	Block action workflows when integrity is unverified.
Change control security	Signed and logged changes to configuration and models.	Require approvals and retain immutable logs.
Incident response linkage	Define what constitutes a cyber incident for twin components.	Treat loss of synchronization or unexplained drift as reportable events.

Sources: WP11-19, WP11-17

7.3 7.3 Auditability is the bridge between models and accountability

Auditability is the bridge between a model output and an accountable operational action. ISO terminology covers stakeholders and life-cycle processes, which implies ongoing evidence requirements, more than initial design documentation. In mining, audit drivers can include safety governance and environmental monitoring expectations, and tailings management provides an example of auditable requirements and monitoring expectations. Even when a twin is not directly used for compliance, the discipline of auditability improves operational trust. Build audit trails that can reconstruct the state: what the sensors reported, how data was transformed, what configuration was active, what model version produced the output, what uncertainty was declared, and what action was taken. Without this chain, a twin is a high-speed opinion generator. With it, the twin becomes a decision system that can be reviewed, improved and governed.

WP11-03, WP11-22, WP11-23

The evidence dossier explicitly notes a measurement gap for audited realized ROI point figures in authoritative sources. This makes auditability even more important internally. If external evidence provides projections and qualitative findings, then operational organizations must build their own evidence through disciplined measurement and audit trails. A twin program that cannot produce reproducible internal evidence will struggle to justify scaling, regardless of how compelling vendor narratives may be. Use the WEF value-at-stake projections as a motivation to set measurement standards, not as a substitute for them. Combine this with literature-reported barriers, especially data quality and interoperability, and treat auditability as a control that detects and corrects those barriers early. This is how governance supports financial and operational accountability without overstating what published evidence can support.

WP11-12, WP11-06, WP11-16

DECISION INSTRUMENT

Audit chain requirements for twin-influenced decisions

A minimum evidence chain that must exist before a twin output can be used in operational action workflows.

TEST	EVIDENCE READING	DECISION RESPONSE
Data provenance	Source systems and timestamps for all inputs.	Reject outputs without provenance.
Transformation log	Documented transformations and feature engineering steps.	Require versioned transformation code and logs.
Model and configuration version	Model version, parameters, and asset configuration state at decision time.	Block action if versions are missing or inconsistent.
Decision record	Who acted, what action, when, and outcome measured later.	Require completion of decision records for continuous improvement.

Sources: WP11-12, WP11-03



08

GATE

The twin readiness gate

A readiness gate prevents premature operational authority by testing whether data, interoperability, models and governance can sustain synchronization and audit under change.

Gate

READINESS GATE IS A DATA-READINESS AND GOVERNANCE TEST, NOT A DELIVERY METHOD | WP11-03

Barrier-driven

GATE CRITERIA DERIVED FROM LITERATURE BARRIERS: DATA, INTEROPERABILITY, COST, 技能 | WP11-16

Architecture lens

USE REFERENCE-ARCHITECTURE LAYERS TO STRUCTURE EVIDENCE AND OWNERSHIP | WP11-04

8.1 8.1 Define readiness as evidence, not enthusiasm

Readiness is the point where an organization can sustain synchronization and decision auditability under real operational change. Literature reviews list recurring barriers: data quality, availability and latency; interoperability of heterogeneous OT and IT systems; integration cost; geological and process variability; and a skills gap. These barriers are not reasons to avoid twins. They are readiness criteria. A readiness gate should therefore test, with evidence, whether a candidate use case meets minimum thresholds for data timing and quality, whether asset identity and configuration are controlled, whether interfaces are stable, and whether people and processes exist to validate and govern models. ISO terminology places the twin in a life-cycle context with stakeholders, which supports using readiness as a controlled decision. If readiness evidence is weak, the correct decision is not to force a twin. It is to invest in the prerequisites and keep outputs advisory.

WP11-16, WP11-03

A second discipline is to respect evidence vintage and type. WEF value-at-stake figures are projections from 2017 to 2025 and must remain labeled as projections. Scenario demand context is explicitly scenario-based. These sources can justify prioritization, but they cannot certify readiness for operational authority. Readiness must be demonstrated locally through tests and audit trails. Use the ISO 23247 layered lens as a structuring tool for readiness evidence: show readiness per layer, from data acquisition through representation and information exchange to consumption and action. This keeps the program from passing readiness based on a strong model in one area while ignoring weak interfaces or weak governance elsewhere. Readiness, in short, is a decision based on test results, not a milestone based on spend or schedule.

WP11-12, WP11-06, WP11-24, WP11-04

DECISION INSTRUMENT

Twin readiness gate: evidence checklist

A gate that must pass before any twin output is granted operational decision authority.

TEST	EVIDENCE READING	DECISION RESPONSE
Synchronization proof	Demonstrated cadence and fidelity for decision-critical variables.	If unproven, restrict to analytics and monitoring only.
Identity and configuration control	Versioned asset identity and configuration baselines with approvals.	If uncontrolled, block operational authority.
Interoperability and exchange stability	Interfaces tested for semantics, timing, and failure behavior.	If unstable, delay scaling and remediate interfaces.
Governance and audit	Decision rights, access controls, and audit chain implemented and tested.	If audit chain is incomplete, do not allow action workflows.

Sources: WP11-01, WP11-16, WP11-17

8.2 8.2 Use staged gates aligned to authority levels

Readiness is not binary because decision authority is not binary. Use a staged gate aligned to the authority ladder described earlier: observe, advise, assist, act. Mining reviews show that human oversight remains common, driven by remote operations and variability, so staged authority matches operational reality. At early stages, the system may only need enough data quality to support monitoring and anomaly detection, with clear uncertainty declarations. At higher stages, the system must meet stronger requirements: stable interfaces, validated models, controlled configuration, secure access, and tested fallback behavior. ISO terminology supports this staged view because it treats the twin as a system with stakeholders and life-cycle processes. Each stage adds stakeholders and increases consequence, so readiness evidence must expand accordingly. This is how you avoid granting automation authority because a visualization looked convincing during a pilot window.

WP11-14, WP11-16, WP11-03

A layered architecture perspective helps define what must be ready at each stage. ISO 23247 partitions twinning systems into layers and explicitly includes information exchange. Even if your implementation differs, the layered lens forces completeness: data acquisition readiness, representation readiness, exchange readiness, and consumption and action readiness. It also aligns with interoperability consensus that treats interoperability as central to automation and integration. If a project passes model validation but fails exchange stability, the readiness gate should block any increase in authority. Similarly, if data access and usage are not governed, the gate should block scale-out across sites or corridors. Stage gates protect the organization from the common failure mode where pilots succeed under manual interventions that cannot be sustained. Readiness should only be declared when the system can perform under normal staffing and normal change rates.

WP11-04, WP11-18, WP11-17

DECISION INSTRUMENT

Staged readiness criteria by authority level

A gate table that ties readiness evidence to the level of operational authority granted.

TEST	EVIDENCE READING	DECISION RESPONSE
Observe readiness	Time alignment, basic quality checks, alert routing, identity binding.	Approve monitoring only; no recommendations without uncertainty labels.
Advise readiness	Model validation evidence, uncertainty template, operator feedback loop.	Approve recommendations with confirmation; log decisions and overrides.
Assist readiness	Controlled configuration, secure approvals, rollback and fallback tests.	Approve bounded actions with human approval and audit.
Act readiness	Proven stability across regimes, cybersecurity controls, incident response integration.	Approve automation only with defined envelopes and continuous monitoring.

Sources: WP11-16, WP11-19, WP11-05

8.3 8.3 Decide when not to build a twin

A readiness gate must also support a defensible decision not to build a twin for a given use case. Literature barriers include high capital and integration cost, skills gaps, and interoperability challenges. If the decision benefit is small or the decision cadence is slow, a synchronized twin may be unnecessary. A well-governed simulation or reporting system may be adequate. ISO terminology helps protect this choice by clarifying that simulation and IoT are distinct concepts. You can invest in data quality and interoperability without claiming a twin, and you can harvest value from those foundations in many ways. The WEF initiative table lists multiple digital initiatives with value-at-stake projections, which reminds leaders that benefits come from a portfolio, not from a single label. Use the readiness gate to allocate capital to the foundations that improve multiple decisions, not to chase the most ambitious twin concept first.

WP11-16, WP11-05, WP11-10, WP11-12

Where a twin is pursued, keep the decision system definition in force. Require that the physical instance is named, that synchronization cadence and fidelity are specified, and that uncertainty is declared. Require that interoperability contracts and governance controls are operational before scaling. Where those requirements cannot be met, keep outputs in an advisory channel and continue to build prerequisites, particularly identity, configuration and interface stability. This preserves credibility and prevents operational teams from being burdened by systems that change faster than they can be validated. It also protects the organization from overstating outcomes in a way that conflicts with evidence limitations noted in the dossier, especially around realized ROI point figures. A disciplined “not yet” decision is a sign of operational maturity, not a lack of ambition.

WP11-01, WP11-17, WP11-12

DECISION INSTRUMENT

Stop or defer decision: twin suitability screen

A screen to decide whether a use case should be a twin, a simulation, or a reporting capability.

TEST	EVIDENCE READING	DECISION RESPONSE
Need for persistent linkage	Decision depends on the evolving state of a specific physical instance.	If no, build simulation or analytics, not a twin.
Cadence requirement	Decision requires synchronized updates faster than manual reporting can support.	If no, defer twin and strengthen data governance first.
Consequence and control	Decision has high consequence and needs audit and approvals.	If yes, require full governance and validation before authority.
Interoperability readiness	Interfaces and semantics can be stabilized across required systems.	If no, prioritize interoperability program and delay twin scope.

Sources: WP11-05, WP11-16, WP11-18

Decision checklist

Use these questions before the next gate, assurance review or capital commitment.

- | | | | |
|-----------|--|-----------|---|
| 01 | State the decision inventory before naming any initiative a digital twin. [WP11-01, WP11-06] | 02 | Name the physical instance and define its boundary for each use case. [WP11-05] |
| 03 | Specify synchronization frequency and fidelity tied to decision cadence. [WP11-01] | 04 | Create a minimum viable asset identity contract and enforce it at ingestion. [WP11-05, WP11-16] |
| 05 | Baseline configuration items that change decision outcomes and place them under change control. [WP11-16, WP11-03] | 06 | Separate measured state, inferred state, forecasts and scenarios in every operational view. [WP11-05, WP11-02] |
| 07 | Adopt an interoperability contract that defines semantics, timing, failure behavior and versioning. [WP11-17, WP11-18] | 08 | Implement data lineage so outputs can be traced to sources and transformations. [WP11-16] |
| 09 | Use an authority ladder and stage gates before allowing any automated actions. [WP11-16, WP11-14] | 10 | Require model validation evidence tied to asset regimes and configuration states. [WP11-16, WP11-15] |
| 11 | Tie cybersecurity controls to decision authority and interface integrity, not to tool categories. [WP11-19, WP11-10] | 12 | For tailings and other critical infrastructure, treat monitoring, alerting and auditability as non-negotiable prerequisites. [WP11-23, WP11-22] |

Evidence ledger 1 of 2

Only dossier rows used in this edition are listed. Concise excerpts identify each registered statement; the source audit retains the complete dossier reference.

ROW	REGISTERED EVIDENCE EXCERPT	REGISTERED SOURCE
WP11-01	Digital twin defined: A digital twin is a virtual representation of real-world entities and processes, synchronized at a specified frequency and fidelity. Definition released 3...	Digital Twin Consortium, "Digital Twin Consortium Defines Digital Twin", 2020
WP11-02	DTC supplement: digital-twin systems use real-time and historical data to represent the past and present and simulate predicted futures; the two constitutive elements are the...	Digital Twin Consortium, 2020
WP11-03	ISO/IEC 30173:2023 Digital twin : Concepts and terminology establishes terminology for digital twin and describes concepts: digital-twin system context, life-cycle processes,...	ISO/IEC 30173:2023 (ISO catalogue)
WP11-04	ISO 23247 Digital twin framework for manufacturing is a four-part series (Part 1 overview and general principles; Part 2 reference architecture; Part 3 digital representation of...	ISO 23247 series (2021), per NIST, "An Analysis of the New ISO 23247 Series of Standards...
WP11-05	ISO/IEC 30173 distinguishes the digital twin from simulation, cyber-physical system, asset administration shell and IoT: a defining property is the persistent, synchronized data...	ISO/IEC 30173:2023 (ISO catalogue)
WP11-06	More than \$425 billion of value for the industry, customers, society and environment over the ten years to 2025; This is the equivalent of 3-4% of industry revenue.	World Economic Forum with Accenture, Digital Transformation Initiative: Mining and...
WP11-07	More than \$320 billion of industry value over the next decade, split as \$190 billion for the mining sector and \$130 billion for the metals sector.	WEF/Accenture, 2017
WP11-09	Safety: around 1,000 lives saved and 44,000 injuries avoided, equating approximately to a 10% decrease in lives lost and a 20% decrease in injuries in the industry.	WEF/Accenture, 2017
WP11-10	Value at stake by digital initiative (industry, ten-year, ~US\$): Integrated Sourcing/procurement ~\$106bn; Connected worker ~\$85bn; Remote Operations ~\$84bn; Autonomous Operations...	WEF/Accenture, 2017
WP11-11	Autonomous Operations detail: machines could create \$56 billion of additional value, of which the bulk of this value (\$47 billion) accrues to the mining sector; in mining, an...	WEF/Accenture, 2017
WP11-12	▲ VINTAGE DISCIPLINE: WP11-06 to -11 are a 2017 forward projection to 2025. The paper cites them as the foundational, decade-old value-at-stake estimate for mining digitalization...	: (usage rule)
WP11-13	A systematic review of AI-driven digital twins in mining operations examined 68 primary studies published 2015:2025, analysing publication trends, research methods, data sources...	Peer-reviewed systematic review (AI-driven digital twins in mining operations),...
WP11-14	A 2024 review of digital-twin systems in mining spans the value chain: mineral exploration, drilling, blasting, loading, hauling, mineral processing and environmental issues; it...	Nasir et al., "Exploring digital twin systems in mining operations: A review", Green and...

Evidence ledger 2 of 2

Only dossier rows used in this edition are listed. Concise excerpts identify each registered statement; the source audit retains the complete dossier reference.

ROW	REGISTERED EVIDENCE EXCERPT	REGISTERED SOURCE
WP11-15	Process digital twin defined in the minerals context: a digital replica of the actual processing of the orebody for a minerals processing plant, using dynamic simulation with...	AusIMM Bulletin, "Digital transformation for minerals processing: the fundamentals (Part..."
WP11-16	Named adoption barriers recurring across the mining digital-twin literature: high capital and integration cost; data quality, availability and latency; interoperability of...	Nasir et al., 2024 (review synthesis)
WP11-17	The Global Mining Guidelines Group (GMG) is a network of mining companies, OEMs, OTMs, research organizations, academics, consultants, regulators and industry associations;...	Global Mining Guidelines Group, interoperability alignment report
WP11-18	GMG's interoperability alignment report presents an industry consensus on interoperability gathered through interviews and workshops with 17 mining companies on six continents,...	GMG, interoperability alignment report
WP11-19	In 2021 GMG and the Digital Twin Consortium (DTC) entered a liaison agreement; DTC supports alignment across GMG workstreams including Interoperability and Data Access and Usage,...	GMG / Digital Twin Consortium liaison announcement, 2021
WP11-20	Deloitte's Tracking the Trends 2026 is the 18th annual edition of the mining-and-metals outlook, released 27 January 2026, exploring ten trends facing the industry over the next...	Deloitte, Tracking the Trends 2026, Mining & Metals, 2026
WP11-21	Tracking the Trends 2026 frames exploration's future as data-first: mining historically focused on ground acquisition and physical prospecting, but the starting point for future...	Deloitte, 2026
WP11-22	The Global Industry Standard on Tailings Management (GISTM) comprises six topic areas, 15 principles and 77 auditable requirements, with the goal of zero harm to people and the...	ICMM, Global Industry Standard on Tailings Management overview
WP11-23	GISTM implementation drives real-time instrumentation with automatic anomaly alerts as part of integrated tailings-facility monitoring systems, and the upgrading of dam monitoring...	ICMM, GISTM overview (implementation)
WP11-24	Copper demand +30% by 2040 (STEPS); announced supply -30% vs projected 2035 demand	Dossier H.3 / WP-04 cleared (IEA, Global Critical Minerals Outlook, 2025, STEPS scenario)
WP11-25	Iron ore 62% Fe benchmark averaged US\$100.2/dmt in 2025; World Bank CMO April 2026 forecast US\$97.0 (2026f) / US\$95.0 (2027f)	Dossier H.1 / WP-04 cleared (World Bank, Commodity Markets Outlook, April 2026)
WP11-26	The productivity/cost pressure context: mining faces declining head grades, deeper deposits and rising input costs, the structural case the WEF DTI value-at-stake was built to...	WEF/Accenture, 2017 (framing) + WP-04 cleared demand rows

Glossary

Digital twin

A virtual representation of real-world entities and processes, synchronized at a specified frequency and fidelity, with persistent linkage to a specific physical instance. [WP11-01, WP11-05]

Synchronization mechanism

The constitutive linkage that keeps the virtual representation aligned with the physical instance using real-time and historical data. [WP11-02]

Frequency and fidelity

The specified update cadence and accuracy needed for a twin to support defined decisions. [WP11-01]

Reference architecture (twinning)

A layered framework for digital twinning systems, including information exchange, described in the ISO 23247 series as analyzed by NIST. [WP11-04]

Interoperability

The ability of heterogeneous systems to exchange information with consistent meaning, treated by GMG as key to success in automation, digitalization and integration initiatives. [WP11-17]

Process digital twin (minerals processing)

A digital replica of ore processing for a plant using dynamic simulation with physical properties and chemical processes at refining steps. [WP11-15]

GISTM

The Global Industry Standard on Tailings Management, described as six topic areas, 15 principles and 77 auditable requirements, with monitoring expectations including real-time instrumentation and anomaly alerts. [WP11-22, WP11-23]

Value at stake (2017 vintage)

A WEF and Accenture projection of potential value from mining and metals digital transformation over the ten years to 2025, not a statement of realized outcomes. [WP11-06, WP11-12]

STEPS scenario

A stated scenario context used for a cleared demand projection and not a forecast of realized demand. [WP11-24]

Skills gap (adoption barrier)

A recurring barrier to mining digital-twin adoption reported in literature reviews, alongside data and interoperability challenges. [WP11-16]

Life-cycle processes and stakeholders (twin context)

Elements explicitly included in ISO terminology for digital-twin systems, used to frame governance and handover requirements. [WP11-03]

Information exchange

A defined concern in the ISO 23247 twinning framework, used to structure interoperability and interface design. [WP11-04]

Data-first exploration (outlook)

An industry outlook statement that the starting point for future discoveries could be data, used as context for decision and data foundations. [WP11-21]

Autonomous operations (2017 projection)

A WEF initiative category with projected value and safety impacts over a decade to 2025, not a realized outcome. [WP11-11, WP11-12]

Asset cybersecurity (2017 projection)

A WEF initiative category with projected value at stake, used as a cue that connectivity raises cyber risk. [WP11-10, WP11-12]

Interoperability alignment report

A GMG synthesis of industry consensus on interoperability based on interviews and workshops with 17 companies on six continents. [WP11-18]

Twin readiness gate

A gate that tests evidence of synchronization, governance, interoperability and validation before granting decision authority, derived from standards and literature barriers. [WP11-03, WP11-16]

Persistent linkage

The property that separates a twin from a one-off simulation run by maintaining synchronized data linkage to a specific instance over time. [WP11-05]

References and limitations

Digital Twin Consortium (Object Management Group program) (2020)

Digital Twin Consortium Defines Digital Twin. Definition released 3 December 2020. [WP11-01, WP11-02]

ISO/IEC JTC 1/SC 41 (2023)

ISO/IEC 30173:2023 Digital twin, Concepts and terminology. Cited from ISO catalogue record; clause text not reproduced. [WP11-03, WP11-05]

National Institute of Standards and Technology (NIST) (n.d. (recorded 2026-))

An Analysis of the New ISO 23247 Series of Standards on Digital Twin Framework for Manufacturing. Used as the archived analysis record describing ISO 23247 parts and architecture. [WP11-04]

World Economic Forum in collaboration with Accenture (2017)

Digital Transformation Initiative: Mining and Metals Industry. Value-at-stake projections to 2025 cited with 2017 vintage. [WP11-06 to WP11-12, WP11-26]

Nasir et al. (Elsevier) (2024)

Exploring digital twin systems in mining operations: A review (Green and Smart Mining Engineering). Value-chain scope and adoption context. [WP11-14, WP11-16]

AusIMM (n.d. (captured 2026-))

Digital transformation for minerals processing: the fundamentals, Part 2 (AusIMM Bulletin). Process digital twin definition in minerals processing context. [WP11-15]

Global Mining Guidelines Group (GMG) (n.d. (captured 2026-))

Interoperability alignment report announcement. Network description and consensus process from 17 companies. [WP11-17, WP11-18]

Global Mining Guidelines Group (GMG) and Digital Twin Consortium (DTC) (2021)

Liaison announcement. Alignment of workstreams including cybersecurity, asset management and data access. [WP11-19]

Deloitte (2026)

Tracking the Trends 2026, Mining and Metals. 18th annual edition; released 27 January 2026; high-level throughline cited from landing page capture. [WP11-20, WP11-21]

ICMM (n.d. (captured 2026-))

Global Industry Standard on Tailings Management overview. Structure and monitoring expectations including instrumentation and anomaly alerts. [WP11-22, WP11-23]

International Energy Agency (IEA) (2025)

Global Critical Minerals Outlook. Cleared scenario row reused; STEPS scenario. [WP11-24]

World Bank (2026)

Commodity Markets Outlook. April 2026 forecast figures. [WP11-25]

USE LIMITATIONS

- WEF value-at-stake figures are a 2017 forward projection to 2025 and are cited only as that projection, not as realized outcomes. [WP11-12, WP11-06]
- ISO/IEC 30173:2023 and ISO 23247 texts are paywalled; citations rely on the ISO catalogue record and a NIST analysis record, without reproducing clause text. [WP11-03, WP11-04]
- The systematic review statistic (68 studies, 2015 to 2025) is taken from indexed search record and published metadata; the full publisher page capture was blocked during archival fetch per dossier note. [WP11-13]
- The evidence base does not provide audited realized ROI point figures for digital twins in mining; the paper avoids inventing such figures and focuses on decision-system controls and readiness criteria derived from standards and reviews. [WP11-16, WP11-12]

EDITION STATUS

This technical paper is an editorial synthesis for decision support. It is not a feasibility study, investment recommendation, legal opinion or project-specific assurance statement.



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