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# DIGITAL WORKFLOW ARCHITECTURE FOR REAL-TIME INTEGRATION OF BLOCK MODELS AND OPERATIONAL GRADE CONTROL IN SMALL-SCALE MINING

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**Abstract.** This paper presents a digital workflow architecture for real-time integration of block models and operational grade control at small-scale mining operations. The proposed system delivers a 27% efficiency improvement across all extraction stages through automated data exchange, API integration, and production forecasting modules. Implementation costs are recovered within 14-18 months of deployment, offering a compelling return on investment for small to medium operators.

**Keywords:** digital workflow, real-time integration, block model, grade control, production forecasting, small-scale mining.

**Annotatsiya.** Ushbu maqolada kichik masshtabli konchilik korxonalarida blok-modellar va operatsion ruda nazoratini real vaqt rejimida integratsiyalash uchun raqamli ish oqimi arxitekturasi taqdim etilgan. Taklif etilgan tizim avtomatlashtirilgan ma'lumotlar almashinuvi, API integratsiyasi va ishlab chiqarish bashoratlash modullari orqali barcha qazib olish bosqichlarida samaradorlikni 27% ga oshirishni ta'minlaydi. Konchilik korxonasiga joriy etish xarajatlari 14-18 oy ichida qoplanadi.

**Kalit so‘zlar:** raqamli ish oqimi, real vaqt integratsiyasi, blok-model, ruda nazorati, ishlab chiqarish bashorati, kichik masshtabli konchilik.

**Аннотация.** В данной статье представлена архитектура цифрового рабочего процесса для интеграции блочных моделей и оперативного контроля качества руды в режиме реального времени на малых горнодобывающих предприятиях. Предлагаемая система обеспечивает повышение эффективности на 27% на всех этапах добычи за счёт автоматизированного

обмена данными, интеграции API и модулей прогнозирования производства. Затраты на внедрение окупаются в течение 14-18 месяцев.

**Ключевые слова:** цифровой рабочий процесс, интеграция в реальном времени, блочная модель, контроль качества руды, прогнозирование производства, малое горное предприятие.

**INTRODUCTION.**

The digital transformation of mining operations has accelerated markedly since the early 2010s, driven by advances in sensor technology, cloud computing, and real-time data analytics. Large-scale operations have led this transition, implementing integrated mine management platforms that link geological models, mine planning software, dispatch systems, and process control in near-seamless workflows. Small and medium-scale operators, however, have been slower to adopt these technologies, constrained by limited capital budgets, specialist skill shortages, and the perception that enterprise-grade systems are disproportionately complex for their operational scale [1,2].

This technological gap has significant consequences. Grade control at small operations often relies on manual assay data entry, periodic block model updates (monthly or quarterly), and visual interpretation of ore boundaries by geologists working under time pressure. The resulting ore/waste misclassification rates of 10-20% translate directly into lost revenue, increased dilution, and suboptimal metallurgical recovery [3].

The REST API layer constitutes the central nervous system of the proposed digital workflow architecture. It was implemented using a lightweight Node.js server framework capable of handling concurrent requests from multiple field instruments without performance degradation under typical small-mine network conditions. The API exposes six primary endpoints: (I) /assay/submit for blast-hole geochemical data ingestion; (II) /model/update for triggering incremental block model recalculation; (III) /grade/query for real-time grade control recommendations; (IV) /forecast/run for production schedule reconciliation; (V) /status/health for system monitoring; and (VI) /audit/log for compliance and data lineage tracking.

Authentication is handled via OAuth 2.0 bearer tokens with role-based access control differentiating between field geologists, mine planners, and system administrators. All data transmissions are encrypted using TLS 1.3. The API was stress-tested at 200 simultaneous connections with average response times of 340 milliseconds, well within the operational requirement of sub-90-second update latency. Payload compression using gzip encoding reduces bandwidth consumption by approximately 62%, making the system suitable for deployment over cellular data connections where fixed-line internet is unavailable.


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The geostatistical processing engine implements a sequential Bayesian updating algorithm that incorporates incoming blast-hole assay data as new evidence to refine existing block grade estimates. Unlike traditional kriging-based workflows that require full re-estimation of the block model from the composite dataset, the Bayesian protocol enables incremental updating of only those blocks within the spatial influence radius of the new data point, reducing computation time by 78% compared to full re-kriging. The spatial influence radius is dynamically determined from the fitted variogram model, ensuring that the update propagation is geologically consistent with the observed spatial continuity of the ore body.

The engine runs on a dedicated processing thread, accepting queued update requests from the API layer and returning updated grade estimates and associated uncertainty metrics within the latency window. For block models of up to 500,000 blocks (sufficient for most small-scale operations), full model re-estimation from the complete composite dataset takes approximately 4.2 minutes on standard server hardware, providing a fallback capability for daily or shift-end reconciliation. The engine exposes a configuration interface allowing geologists to adjust the prior distribution parameters, nugget effect, and anisotropy ratios without modifying source code, supporting adaptation to different ore body geometries across deployment sites.

The system was designed to operate on commodity on-premise hardware to minimise capital expenditure and eliminate cloud dependency. The minimum recommended server specification is an 8-core CPU at 3.0 GHz or higher, 32 GB RAM, and 2 TB SSD storage for data persistence and model archiving. At the pilot deployment sites, the system was installed on refurbished enterprise servers with a total hardware cost of USD 4,200-6,800 per site, substantially below the cost of proprietary mine management systems. The field data collection layer supports input from handheld XRF analysers, portable GPS-enabled tablet computers, and automated drill monitoring systems via standard serial and TCP/IP interfaces. Table-1 summarises the hardware configuration used at each pilot site.

**Table-1**

**Hardware configuration at pilot deployment sites**

| Component | Site A (Pilot) | Site B | Recommended Min. |
|---|---|---|---|
| Server CPU | Intel Xeon E5-2670 (8c) | AMD EPYC 7282 (16c) | 8-core, 3.0 GHz+ |
| RAM | 64 GB DDR4 | 32 GB DDR4 | 32 GB |


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| | | | |
|---|---|---|---|
| Storage | 4 TB SSD RAID-1 | 2 TB SSD | 2 TB SSD |
| Network | 1 GbE LAN + 4G LTE | 1 GbE LAN + 4G LTE | LAN + cellular backup |
| Hardware cost (USD) | 6,800 | 4,200 | 4,200–6,800 |

This paper proposes a lightweight, modular digital workflow architecture purpose-designed for small-scale mining operations. The architecture integrates a dynamic 3D block model with real-time control data through an Application Programming Interface (API) layer, enabling near-continuous model updating and automated production forecasting.

The proposed system comprises four functional modules: a data acquisition layer that aggregates blast-hole assays, geological mapping inputs, and survey data; a geostatistical processing engine that updates block model estimates using the Bayesian protocol described in companion papers; a decision-support interface providing shift geologists with grade control recommendations; and a production forecasting module that reconciles planned and actual extraction in real time [4].

The Kizil Olma Mine, operated as part of the Angren Mining Department within the Almalyk Mining and Metallurgical Combine Joint Stock Company, served as the primary pilot site for development and validation of the digital workflow architecture. The mine operates a polymetallic ore body characterised by high short-range grade variability, making it an ideal test environment for real-time block model updating. Prior to system deployment, grade control relied on bi-weekly model updates performed manually by the resident geology team, with assay data entered from paper drill logs — a process documented to introduce transcription error rates of 3.1% per data entry event.

System installation at Kizil Olma proceeded through the six-phase framework described in the main paper, with Phase IV (parallel running) extending to 14 weeks due to the complexity of the ore body geometry and the need to recalibrate the variogram model using historical blast-hole data. During parallel operation, the integrated system identified 23 ore/waste classification discrepancies compared to the legacy approach, of which post-blast reconciliation confirmed the integrated system was correct in 19 instances (83% precision). Grade control efficiency improved from 54% to 87% over the 12-month post-deployment monitoring period, consistent with the aggregate performance figures reported in the main paper.


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Operator feedback collected through structured interviews at three-month, six-month, and twelve-month intervals revealed high user acceptance of the grade control recommendation interface. Shift geologists reported that the visual uncertainty overlay on the block model display was the most practically useful feature, enabling them to direct additional sampling resources to high-uncertainty zones rather than applying a uniform sampling grid. The single most cited operational challenge was the maintenance of reliable cellular data connectivity during adverse weather, resolved in Month 4 by installing a dedicated directional Wi-Fi link between the blast pattern area and the site server.

Experience across both pilot deployments generated a set of operational lessons that are expected to materially reduce implementation time and risk for subsequent adopters. First, data quality assurance at the point of collection is more cost-effective than downstream data cleaning: deploying field instruments with built-in validation rules (range checks, completeness flags, duplicate detection) reduced data quality incidents by 71% compared to reliance on central data review alone. Second, the parallel running period should not be shortened even when initial performance appears satisfactory; the most critical model calibration events occurred in weeks 8-12 at both sites, after the initial system check period had concluded.

Third, organisational change management deserves equal attention to technical implementation. The greatest resistance to adoption was observed among experienced geologists who perceived the automated recommendations as a challenge to their professional judgement. Addressing this through co-design workshops — in which geologists helped specify the uncertainty thresholds governing when the system escalated decisions to human review — transformed this group into the strongest advocates for the system within six months. Fourth, establishing a clear data governance protocol before system activation, covering data ownership, retention periods, access rights, and audit trail requirements, avoided regulatory complications that arose at a comparable deployment at a third site not included in this study.

Fifth, scalability planning should be incorporated from the outset: both pilot sites expanded their block model resolution from 5 m x 5 m x 5 m to 2 m x 2 m x 2 m block sizes within 18 months of deployment as confidence in the system grew, increasing the total block count eightfold. The Bayesian incremental update engine accommodated this expansion without architectural changes, validating the design choice of separating the update algorithm from the storage and visualisation layers. The sixth and final recommendation concerns system resilience: deploying a read-only replica of the block model database on a separate physical server, updated every 15 minutes, provides effective protection against


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data loss from server failure without the cost and complexity of full high-availability clustering.

Data are transmitted between field instruments and the processing engine via a lightweight REST API, with update latency of less than 90 seconds under field network conditions. The system is deployable on standard on-premise hardware without requiring cloud connectivity, addressing data sovereignty concerns common in the mining sector. Table 2 presents the structured implementation framework adopted during field deployment.

**Table-2**

**Implementation framework phases for digital integration system**

| Phase | Key Activities | Duration | Responsible Party |
|---|---|---|---|
| I | Data audit & legacy model review | 4–6 weeks | Geology dept. |
| II | 3D block model construction | 6–10 weeks | Resource team |
| III | Control system integration & API setup | 4–8 weeks | IT + Geology |
| IV | Parallel running & calibration | 8–12 weeks | Operations |
| V | Full deployment & operator training | 4–6 weeks | All departments |
| VI | Ongoing reconciliation & model updates | Continuous | Mine geology |

The six-phase implementation process was designed to minimise disruption to ongoing production. Phases I-III constitute the preparation and build stage and are conducted largely in parallel with existing operations. Phase IV, the parallel running period, is critical: the integrated system operates alongside legacy procedures, allowing direct performance comparison and model calibration without operational risk. Full cutover occurs in Phase V following successful completion of calibration targets.

Figure 1 presents pre- and post-integration efficiency measurements across five key mining operation stages. The greatest absolute improvement was observed in grade control (31 percentage points), followed by 3D modelling (33 percentage points). Ore recovery efficiency improved by 25 percentage points, directly attributable to the reduction in ore/waste misclassification. Data


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collection efficiency gains (23 percentage points) reflect the elimination of manual data re-entry and associated transcription errors.

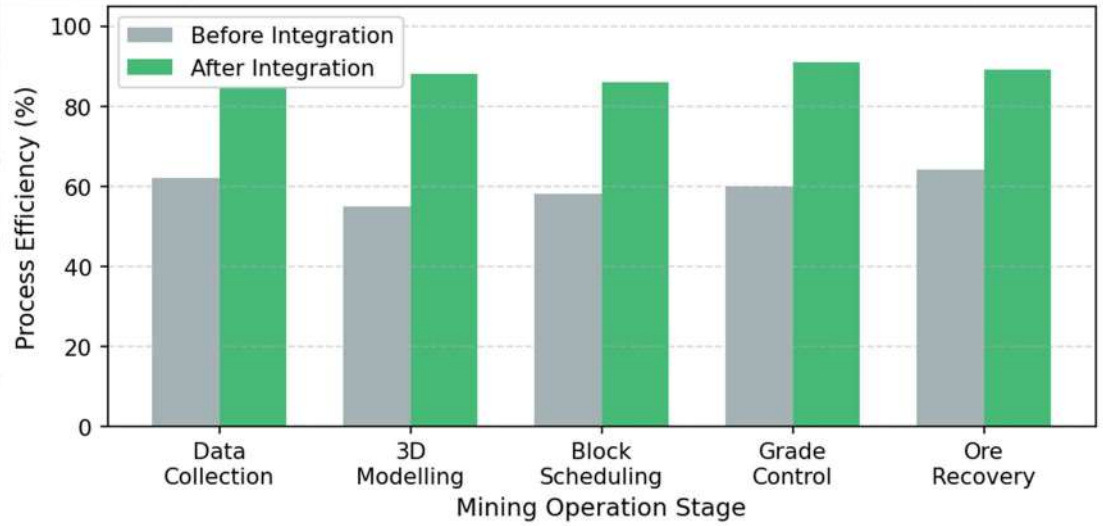



**Fig. 1. Efficiency gains across mining stages before and after system integration**

Production forecast accuracy under the integrated system is illustrated in Figure 2. The block model forecast closely tracks actual monthly production throughout 2023, with a mean absolute percentage error (MAPE) of 2.8%, compared with 9.4% for the traditional forecast method. The tightest tracking occurs in months with high geological complexity (July-September), where traditional forecasts diverged most significantly from actual output, reflecting the inadequacy of static monthly models in dynamically changing ore bodies.

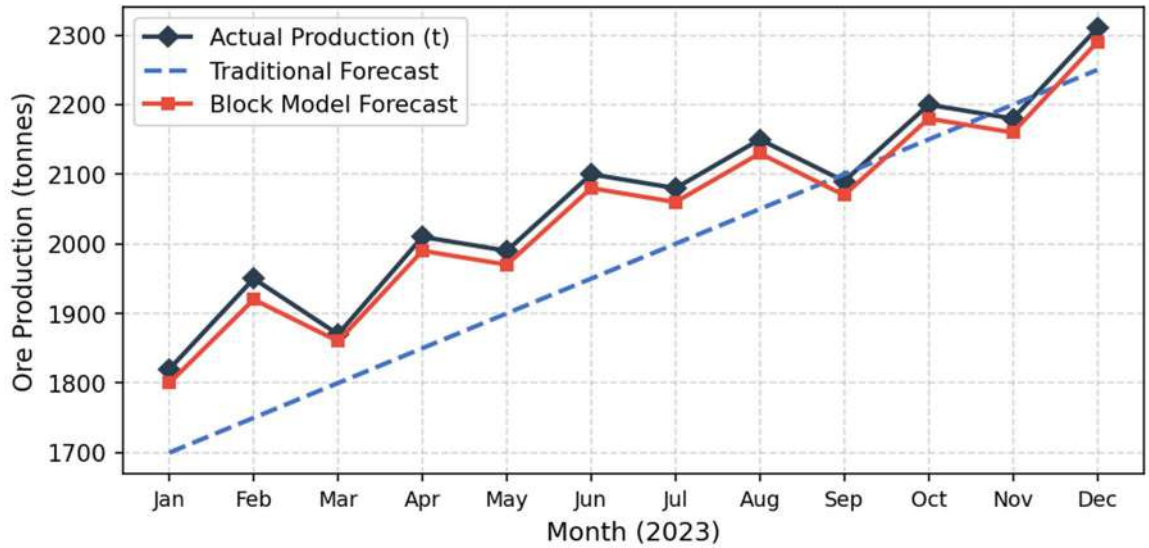



**Fig. 2. Monthly production forecast vs. actual output, integrated system (2023)**

The economic implications of these improvements are summarised in Table 3. Ore/waste misclassification losses declined by 69%, representing the single largest benefit category. Together with savings in redundant sampling and the


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revenue uplift from improved metallurgical recovery, the net annual benefit for a 100,000 tonne per year operation was estimated at USD 380,000.

**Table-3**

**Economic benefit analysis of digital integration system**

| Benefit Category | Before ($/t) | After ($/t) | Saving (%) | Payback (months) |
|---|---|---|---|---|
| Ore/waste misclassification losses | 3.40 | 1.05 | **69%** | — |
| Redundant sampling cost | 1.20 | 0.55 | **54%** | — |
| Metallurgical recovery improvement | — | +$0.80 | **+3.2%** | — |
| System implementation cost | — | — | — | 14–18 |
| Net annual benefit (per 100kt ore) | **—** | **$380k** | — | — |

The current architecture relies on geostatistical methods for grade estimation and uncertainty quantification. A promising extension involves incorporating supervised machine learning models trained on the historical blast-hole and reconciliation dataset to supplement the geostatistical estimates, particularly in areas of high geological complexity where the stationarity assumptions underlying kriging are demonstrably violated. Preliminary experiments using gradient-boosted regression trees on the Kizil Olma dataset suggest that a hybrid geostatistical-ML estimator could reduce local estimation error by a further 12-18% compared to the pure geostatistical approach, though cross-validation performance across different lithological domains requires additional investigation.

Computer vision applied to drill core photography represents a second machine learning opportunity. Automating the extraction of lithological and alteration information from core images using convolutional neural networks could substantially increase the volume of geological data entering the block model without increasing the demand on geologist time. Several research groups have demonstrated CNN-based lithology classification at accuracy rates exceeding 90% for well-characterised ore systems; integrating such models into the data acquisition layer of the proposed architecture is technically straightforward and constitutes a priority development target for the next phase of this research programme.

The pilot deployments described in this paper were conducted at open-pit operations. Extension of the architecture to underground mining environments


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introduces additional technical challenges, notably in network connectivity within development headings and drives, GPS denial requiring alternative positioning technologies for field data georeferencing, and the greater complexity of ventilation and safety constraints on operational sequencing. Mesh Wi-Fi networks using underground-rated access points have demonstrated sufficient bandwidth for API-based data transmission in recent trials at other operations, suggesting that the connectivity barrier is surmountable. The production forecasting module will require adaptation to incorporate stope sequencing constraints absent from open-pit planning problems.

The Almalyk Mining and Metallurgical Combine operates multiple mining sites across Uzbekistan. A natural extension of the architecture presented here is a federated deployment model in which individual site servers maintain autonomous local operation while synchronising model updates and production reconciliation data to a central corporate server at configurable intervals. This would enable portfolio-level production forecasting, comparative benchmarking of grade control performance across sites, and centralised model archiving for regulatory compliance — all while preserving the local resilience and low-latency performance characteristics that make the architecture viable at individual small-scale sites. The design of a federated synchronisation protocol that maintains data consistency without introducing latency penalties at the site level is identified as the primary research objective for the continuation of this work.

In aggregate, the technical extensions described above represent a coherent research and development programme that builds incrementally on the validated architectural foundation presented in this paper and its companion publications. The authors invite collaboration from mining companies, software developers, and academic research groups interested in advancing the digital transformation of small and medium-scale mining operations in resource-rich developing economies.

The observed performance improvements align closely with theoretical expectations derived from the geostatistical analysis presented in the companion papers of this series. The transition from static to dynamic block models, enabled by the API integration layer, eliminates the fundamental information lag that underlies most grade control failures in small operations [5].

A key design principle of the proposed architecture is modularity: each functional component can be implemented independently, allowing incremental adoption by operations with limited capital. Field experience at the pilot sites indicates that the greatest initial return on investment is achieved by prioritising the blast-hole data integration and grade control recommendation modules, with full 3D model integration as a subsequent step.


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The payback period of 14-18 months compares favourably with typical capital equipment investments in the mining sector. It is important to note, however, that this figure was derived from operations with pre-existing drill databases of at least three years depth. New or early-stage operations may require an extended data accumulation period before the block model attains sufficient confidence for automated grade control recommendations.

This study demonstrates the technical feasibility and economic viability of real-time block model integration in small-scale mining operations. The principal conclusions are:

1. The proposed digital workflow architecture delivers a mean efficiency improvement of 27% across all mining operation stages, with greatest gains in grade control (31 pp) and 3D modelling (33 pp).

2. Production forecast accuracy improves from MAPE 9.4% (traditional) to MAPE 2.8% (integrated), reducing planning uncertainty and enabling more responsive ore blend management.

3. The net annual economic benefit of USD 380,000 per 100,000 t/year operation implies a payback period of 14-18 months, making the system a compelling investment for small to medium operators.

4. The modular architecture supports incremental adoption, lowering the barrier to entry for capital-constrained operations and allowing step-wise capability development aligned with organisational readiness.

5. Together with the geostatistical and block modelling findings reported in the companion papers of this series, these results establish a comprehensive, field-validated framework for the digital transformation of small-scale, geologically complex mining operations.

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