The Role of Modern Technologies (Mixed-Integer Linear Programming, Big Data Analytics, and Artificial Intelligence) in Improving Resource Allocation, Cost Accounting Accuracy, and Production Scheduling in Iraqi Industrial Companies: An Informationalism Approach

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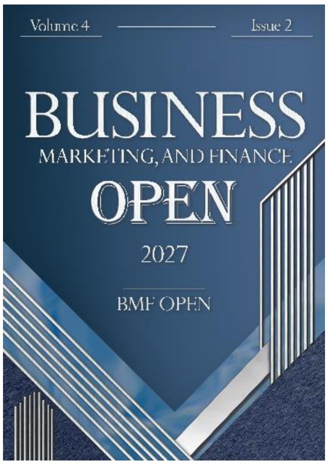

Citation: Alameri, A., Rezazade, J., & Sepasi, S. (2027). The Role of Modern Technologies (Mixed-Integer Linear Programming, Big Data Analytics, and Artificial Intelligence) in Improving Resource Allocation, Cost Accounting Accuracy, and Production Scheduling in Iraqi Industrial Companies: An Informationalism Approach. *Business, Marketing, and Finance Open*, 4(2), 1-29.

Received: 01 March 2026
Revised: 08 July 2026
Accepted: 16 July 2026
Initial Publication: 17 July 2026
Final Publication: 01 March 2027

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Abstract: This study aims to examine the role of three modern technologies—mixed-integer linear programming, big data analytics, and artificial intelligence—in improving cost accounting calculations in Iraqi industrial companies by adopting informationalism as a key strategy. The research employed an applied design based on mathematical modeling and the analysis of real-world data obtained from four industrial units—the Kufa Cement Plant, the Najaf Cement Plant, the Baghdad Soft Drinks Company, and the Iraqi Carpet Company—during the 2020–2024 period. The findings indicate that applying the mixed-integer linear programming model reduced unit costs by between 4% and 88% and optimized resource allocation. Big data analytics reduced cost fluctuations by up to 82%, improved forecasting accuracy by up to 86%, and contributed to cumulative profit growth of up to 64%. Artificial intelligence also reduced unplanned downtime by between 4% and 13%, resulting in a reduction of up to 10.6% in unit costs. The results demonstrate that the effects of these technologies differed across industries. In capital-intensive industries, particularly cement production, their effects were more evident in cost reduction, whereas in labor-intensive industries, particularly carpet manufacturing, their effects were more pronounced in reducing cost variability and improving measurement accuracy. Overall, the systematic integration of these three technologies within an informationalism framework enhances cost accounting accuracy, strengthens the efficiency of managerial decision-making, and is recommended as a practical strategy for industrial organizations in developing economies.

Keywords: modern technologies, mixed-integer linear programming, big data analytics, artificial intelligence, cost accounting, informationalism, Iraqi industrial companies, managerial efficiency.

1. Introduction

Industrial organizations increasingly operate in environments characterized by volatile input prices, complex production processes, resource constraints, intensified competition, and growing demand for timely and reliable accounting information. Under these conditions, conventional cost-accounting systems frequently prove insufficient because they rely on retrospective records, simplified allocation bases, and periodic reporting procedures that may not accurately reflect the actual consumption of resources across production activities. The problem is particularly significant in developing industrial economies, where firms often face fragmented information systems, unstable energy and material supplies, limited automation, and weak integration between production, accounting, and managerial decision-making. Consequently, managers may receive cost information that is delayed, excessively aggregated, or distorted by arbitrary allocations of indirect expenses. Such deficiencies can impair production scheduling, pricing, capacity planning, inventory management, profitability analysis, and the evaluation of operational efficiency. The informational value of accounting data therefore depends not only on compliance with formal accounting procedures but also on the capacity of the underlying information system to capture economic events accurately, process large volumes of operational data, and translate them into decision-relevant measures. This concern is consistent with the broader accounting literature showing that the relevance of financial information may deteriorate when conventional reporting systems fail to represent the economic realities of increasingly complex organizations [1]. In this context, modern analytical technologies—including mixed-integer linear programming, big data analytics, artificial intelligence, data mining, and automated activity-based costing—offer an opportunity to transform cost accounting from a static recording function into an integrated informational infrastructure for real-time operational management.

The theoretical foundation of this transformation can be understood through informationalism, which regards information generation, processing, transmission, and application as central determinants of organizational productivity and managerial effectiveness. From this perspective, industrial competitiveness depends increasingly on the organization’s ability to convert dispersed operational observations into structured information and to use that information in resource-allocation decisions. Accounting information occupies a central position within this framework because it connects production activities, resource consumption, financial outcomes, managerial control, and external evaluation. The importance of information in controlling organizational behavior is also central to agency theory. The separation of ownership and control creates information asymmetry between managers and other stakeholders, enabling managers to pursue decisions that may not maximize organizational value [2]. Agency problems become particularly pronounced when managers control large amounts of discretionary resources or free cash flow without sufficiently effective monitoring mechanisms [3]. Earlier evidence concerning firms with substantial free cash flow similarly indicates that inefficient resource deployment may persist when governance and information systems do not impose adequate discipline [4]. Within industrial organizations, inaccurate product costs and weak production information may create comparable agency problems by allowing resource waste, inefficient scheduling, idle capacity, and cost overruns to remain hidden. Modern cost technologies can reduce these asymmetries by linking accounting measures more directly to physical production, resource usage, equipment status, and market demand.

The value of high-quality accounting information is also evident in capital-market and valuation research. Earnings and book values provide fundamental inputs into firm valuation, but their usefulness depends on the reliability of the accounting processes through which they are generated [5]. Similarly, capital-market evidence suggests that investors may fail to fully distinguish between the cash-flow and accrual components of earnings, thereby creating valuation errors when accrual quality is weak [6]. Earnings attributes, including reliability, persistence, predictability, and smoothness, are associated with the cost of equity because firms with less informative earnings expose investors to greater information risk [7]. Accounting conservatism also affects the timeliness with which economic gains and losses are reflected in reported performance, particularly through the more immediate recognition of unfavorable outcomes [8]. Although these studies primarily concern external financial reporting, their implications extend to industrial cost accounting. Product costs are embedded in inventory valuation, cost of goods sold, gross profit, operating margins, and managerial performance indicators. Errors in assigning raw-material, energy, labor, maintenance, depreciation, and overhead costs can therefore propagate from the production system into financial statements, internal forecasts, and strategic decisions. Improving cost-accounting accuracy is thus not merely an operational issue; it contributes to the overall quality and relevance of organizational reporting.

The literature on earnings management further demonstrates how weaknesses in measurement systems can affect accounting outcomes. Managers may exploit accounting discretion to alter reported performance through accrual choices, operating decisions, or classification practices. The Jones model provided an influential empirical method for estimating discretionary accruals and detecting possible earnings manipulation [9], while subsequent research refined this approach and demonstrated the importance of distinguishing normal accruals from discretionary components [10]. Research on accrual quality has further shown that estimation errors arising from uncertainty in working-capital adjustments reduce earnings reliability even when deliberate manipulation is absent [11]. Methodological reviews have emphasized that earnings-management research must distinguish measurement error from intentional managerial discretion and carefully align empirical models with the economic context being studied [12]. Dechow and Skinner likewise argued that interpretations of earnings management differ across academic, regulatory, and practitioner perspectives, partly because the boundary between permissible judgment and opportunistic reporting is not always clear [13]. These observations are relevant to cost accounting because deviations in unit costs may arise from manipulation, inappropriate allocation rules, incomplete data, operational noise, or forecasting error. Modern technologies can help distinguish among these sources by integrating accounting records with production volumes, machine hours, energy consumption, downtime, and resource flows.

Research has also documented the persistence and temporal dynamics of managed earnings. Firms may maintain extended sequences of earnings increases or avoid unfavorable reporting outcomes through accounting and operating choices [14]. Evidence from the periods before and after the Sarbanes–Oxley Act shows that managers may substitute real activities manipulation for accrual-based earnings management when regulatory constraints change [15]. More recently, evidence from an emerging banking market has demonstrated that earnings-management behavior can persist over time and that specialized indicators may be needed to identify systematic rather than isolated distortions [16]. These findings reinforce the need for continuous, data-driven monitoring rather than reliance on annual or manually prepared cost reports. A real-time system based on big data analytics and artificial intelligence can identify abnormal variations as they occur, compare them with historical patterns, and alert managers before inaccurate cost signals become embedded in production, pricing, or financial-reporting decisions.

Corporate governance research provides additional support for the importance of reliable information and effective monitoring. Board composition has been associated with the likelihood of financial-statement fraud, suggesting that independent oversight can constrain opportunistic reporting [17]. Audit committees with stronger independence and expertise have similarly been linked to lower levels of earnings management [18]. Meta-analytic evidence confirms that governance mechanisms can influence the extent of accounting discretion, although their effectiveness varies across institutional and organizational settings [19]. Studies in emerging and Latin American markets likewise show that ownership structure, board characteristics, and institutional context affect the relationship between governance and earnings management [20]. Internal control regulation can also improve reporting quality by formalizing control procedures and strengthening accountability for information production [21]. In industrial settings, technological systems can complement these formal mechanisms by producing traceable, verifiable, and timely cost information. Sensors, digital production logs, automated cost drivers, and algorithmic alerts create an auditable data trail that reduces reliance on subjective estimates and increases the ability of managers, auditors, and boards to investigate deviations.

External auditing represents another important safeguard for accounting quality. Firms audited by higher-quality auditors generally exhibit lower levels of opportunistic accruals, indicating that effective verification constrains aggressive reporting [22]. Nevertheless, external audits are generally periodic and primarily focused on the fairness of financial statements rather than on continuous operational optimization. Consequently, they cannot substitute for an internal cost-information architecture capable of identifying resource waste, production bottlenecks, abnormal downtime, or inaccurate overhead assignments in real time. The integration of artificial intelligence and big data analytics extends the monitoring function from ex post verification to predictive and preventive control. This capability is particularly important in industrial environments where operational events immediately affect product costs and where delayed detection can result in cumulative financial losses.

The monitoring role of banks and other financial intermediaries offers another conceptual foundation for data-intensive organizational control. Financial intermediation theory explains that banks can serve as delegated monitors by gathering private information and supervising borrowers on behalf of dispersed investors [23]. Banks' reputational incentives may also improve the credibility of monitoring in debt relationships [24]. The distinction between informed insiders and less-informed outside lenders further suggests that access to superior information can improve monitoring but may also create informational rents or dependence [25]. The Japanese main-bank system illustrates how close bank–firm relationships can support monitoring, restructuring, and coordination, particularly under conditions of financial distress [26]. Evidence from Japanese corporate groups also indicates that close banking relationships can mitigate financing constraints and influence firms' investment behavior [27]. Recent evidence shows that bond investors may rely on the informational and monitoring activities of main banks, confirming that delegated monitoring remains relevant in contemporary financial systems [28]. These theories are pertinent to industrial information systems because both bank monitoring and technology-based cost control depend on the collection, interpretation, and disciplined use of information.

The presence of bank-affiliated directors on corporate boards provides a more direct connection between monitoring, accounting policy, and operational decision-making. Such directors may reduce information asymmetry by transferring financial expertise, facilitating access to external financing, and strengthening supervision. Corporate networks created through banks and interlocking directorships can influence governance practices and the circulation of information across organizations [29]. Bank-appointed directors have been shown to affect corporate cash holdings, suggesting that they influence liquidity management and resource-allocation policies [30]. Bankers serving on boards may also shape executive incentives and managerial risk-taking [31]. Evidence concerning bank ownership indicates that close bank relationships can affect earnings quality, although the direction and magnitude of the effect depend on institutional incentives and monitoring strength [32]. Affiliated bankers have also been associated with more conservative accounting practices, implying that creditor-oriented monitoring can accelerate the recognition of risk and constrain optimistic reporting [33]. More recent evidence indicates that bank-affiliated directors can improve financial-reporting quality by strengthening oversight and reducing informational opacity [34], while other research shows that such directors may influence specific accounting policies, including corporate tax avoidance [35]. Together, these findings demonstrate that access to specialized information and analytical expertise can materially affect accounting choices and resource-management outcomes.

However, monitoring relationships are not universally beneficial. Bank-affiliated directors may face conflicts between protecting creditor interests and maximizing shareholder value, and close financial relationships may encourage risk avoidance or private-benefit extraction. The effectiveness of monitoring therefore depends on governance structures, legal protection, incentives, and the quality of available information. Cross-country research demonstrates that investor protection and enforcement institutions shape corporate governance practices and constrain expropriation by controlling parties [36]. Financial reporting and debt contracting are also closely intertwined because accounting information is used to design covenants, evaluate performance, and reduce conflicts between borrowers and lenders [37]. In countries where governance institutions and information infrastructures are less developed, internal technological systems may become especially important because they can partially compensate for weak external monitoring by creating standardized and verifiable operational information.

The implications of information quality also extend to corporate investment and risk. Traditional asset-pricing research establishes that risk and expected return are systematically related, making the accurate measurement of performance and uncertainty essential to capital allocation [38]. Firm-specific risk can influence investment decisions when managers are insufficiently diversified or face private exposure to company outcomes [39]. In industrial companies, inaccurate cost and production data can magnify perceived uncertainty, discourage investment, and lead to inefficient capacity decisions. Conversely, optimization and predictive analytics can reduce uncertainty by providing managers with scenario-based estimates of resource requirements, production costs, and expected demand. These technologies can therefore improve both short-term operating decisions and long-term capital planning.

Nonfinancial performance and corporate responsibility may also affect accounting behavior. Corporate social responsibility has been associated with earnings-management practices, although the relationship may reflect either ethical commitment or reputational strategies [40]. Environmental performance is similarly related to earnings management because managers may use accounting discretion to shape stakeholders' perceptions of sustainability outcomes [41]. These issues are particularly important in cement, beverage, and textile production, where energy use, material waste, emissions, water consumption, and defective products have significant financial and environmental consequences. A technologically integrated cost system can connect environmental resource consumption with product costs, allowing managers to identify waste and incorporate sustainability-related information into production decisions. Big data analytics can detect abnormal energy consumption or material loss, while artificial intelligence can anticipate equipment failures that would otherwise increase waste, downtime, and environmental burdens.

Technological change in the financial sector further demonstrates the organizational value of data integration and automation. Financial-technology adoption has been associated with bank profitability in Arab emerging markets, suggesting that digital systems can improve efficiency, service delivery, information processing, and managerial responsiveness [42]. Although industrial manufacturing differs from banking, the underlying mechanism is comparable: digital technologies create value when they reduce information-processing costs, improve forecasting, support faster decisions, and integrate previously fragmented organizational functions. For Iraqi industrial companies, the adoption of mixed-integer linear programming, big data analytics, and artificial intelligence may therefore generate benefits beyond simple cost reduction. These technologies can create an informational platform through which production, accounting, maintenance, demand forecasting, and managerial control operate as interconnected components.

Mixed-integer linear programming is particularly suitable for industrial resource-allocation problems because it can optimize continuous decisions, such as production quantities and material usage, while simultaneously addressing discrete decisions, such as whether a production line should operate, whether maintenance should be scheduled, or whether a specific production configuration should be selected. By incorporating constraints related to capacity, labor, materials, energy, demand, inventory, and downtime, MILP can identify production plans that minimize total cost while preserving operational feasibility. In cost accounting, its importance lies not only in identifying the least-cost production combination but also in revealing how shared resources and indirect costs should be assigned across products and production stages. This feature is highly relevant to cement manufacturing, where clinker production and final grinding consume different combinations of energy, maintenance, labor, and equipment capacity. It is likewise relevant to beverage and carpet production, where packaging, marketing, labor intensity, and product diversity can distort conventional overhead allocations.

Big data analytics complements optimization by improving the quality of the information supplied to the model. Industrial datasets contain seasonal trends, sudden disruptions, missing observations, outliers, nonlinear relationships, and operational noise. Descriptive statistics alone may not adequately distinguish normal cost variability from abnormal deviations. Clustering, regression analysis, correlation analysis, anomaly detection, and time-series methods can identify latent cost patterns, classify comparable operations, and improve the estimation of future resource requirements. The benefits can be assessed through changes in cost variability, measurement error, forecasting error, profit growth, and managerial efficiency. This analytical orientation reflects the broader accounting principle that high-quality information should faithfully represent underlying economic activity rather than mechanically maximize statistical association. The distinction is important because an apparently strong relationship between production and cost may be artificial if both variables are contaminated by measurement errors or exceptional events.

Artificial intelligence further extends the system from retrospective analysis to adaptive decision-making. Deep-learning models can process large and multidimensional production streams, while reinforcement-learning algorithms can adjust resource allocation or scheduling policies in response to changing conditions. Predictive-maintenance applications can identify patterns preceding equipment failure and allow managers to intervene before unplanned downtime occurs. In cost-accounting terms, this capability improves the measurement of actual resource consumption by reducing abnormal stoppages, separating avoidable downtime costs from normal production costs, and producing more stable cost estimates. The benefit of artificial intelligence may therefore appear either as a direct reduction in unit cost or as an improvement in the accuracy and consistency of cost measurement. This distinction is crucial because the technology may reveal previously hidden costs rather than merely lowering reported expenses.

Despite the conceptual relevance of these technologies, empirical evidence concerning their integrated application in Iraqi industrial companies remains limited. Existing accounting research has extensively examined earnings quality, governance, bank monitoring, audit quality, accrual measurement, and financial-reporting incentives, but considerably less attention has been devoted to the combined use of mathematical optimization, big data analytics, and artificial intelligence for real-time industrial cost accounting. Moreover, findings from developed markets may not be directly transferable to Iraqi manufacturing because industrial firms in Iraq operate under distinctive conditions involving infrastructure constraints, energy instability, administrative complexity, uneven digitalization, and substantial variation in production capacity. An applied investigation based on actual cost and production records is therefore necessary to determine whether these technologies can improve resource allocation, cost-accounting accuracy, production scheduling, forecasting reliability, profitability, and managerial efficiency within this context.

Accordingly, the aim of this study is to examine the role of mixed-integer linear programming, big data analytics, and artificial intelligence, within an informationalism framework, in improving resource allocation, cost-accounting accuracy, production scheduling, cost control, profitability, and managerial decision-making in selected Iraqi industrial companies during 2020–2024.

2. Methodology

In terms of its purpose, the present study is applied research, while in terms of its nature and methodological orientation, it combines quantitative analytical approaches with mathematical modeling. Using real-world data from Iraqi industrial companies, the study seeks to design and test an integrated model for the real-time control of accounting costs based on the integration of modern technologies, including mixed-integer linear programming, data mining, artificial intelligence, and activity-based costing. Informationalism serves as the central strategy and overarching framework governing the proposed model. The statistical population consisted of Iraqi industrial companies, particularly cement-manufacturing companies. The study sample was selected purposively and included the Iraqi State Company for Cement and two of its affiliated plants, namely the Kufa Cement Plant and the Najaf Al-Ashraf Cement Plant. The cement industry was selected because of its extensive volume of data, complex cost structure, and the researcher's access to the companies' financial and production information.

The data used in this study were real-world operational and financial data classified into four main categories and collected from January 2020 to December 2024. Production-process data included production volume measured in tons, downtime measured in hours, and the quantity of defective products measured in tons. Cost accounting records included direct costs, indirect costs, and total costs, all measured in Iraqi dinars. Resource-consumption reports included the consumption of raw materials, fuel and lubricants, water, and electricity. Market-demand data included monthly market demand measured in tons and the market price measured in Iraqi dinars per ton. All data were collected through field visits and reviews of the official accounting records of the selected companies. Duplicate, missing, and outlier observations were identified and removed, and data obtained from different sources were transformed into a standardized format. Moreover, the effects of the COVID-19 pandemic during the 2020–2022 period were controlled through Monte Carlo simulation and sensitivity analysis.

To optimize resource allocation and production scheduling, a mixed-integer linear programming model was formulated as shown in Equation 1:

$$\min Z = \sum_{i=1}^{I} \sum_{t=1}^{T} (c_{it}x_{it} + h_{it}s_{it} + p_{it}u_{it} + f_{it}y_{it}) \qquad (1)$$

subject to:

$$s_{i,t-1} + x_{it} - d_{it} = s_{it} - u_{it}, \forall i, t$$

$$\sum_{i=1}^{I} a_{ir}\, x_{it} \le R_{rt}, \forall r, t$$

$$0 \le x_{it} \le M_{it} y_{it}, \forall i, t$$
$$x_{it}, s_{it}, u_{it} \ge 0, y_{it} \in \{0,1\}.$$

In this formulation, Zrepresents the total production-system cost; x_{it}denotes the production quantity of product $i$during period t; s_{it}represents inventory; u_{it}denotes unmet demand or production shortage; and $y_{it}$is a binary decision variable indicating whether the relevant production line is active. Furthermore, c_{it}, h_{it}, p_{it}, and f_{it}represent unit production cost, inventory-holding cost, shortage cost, and fixed operating cost, respectively. The parameter a_{ir}represents the amount of resource $r$required to produce one unit of product i, whereas R_{rt}denotes the available quantity of resource $r$during period t. Finally, d_{it}represents demand and $M_{it}$is an upper-bound parameter associated with production capacity.

Hidden patterns within the cost data were extracted using clustering techniques to classify similar processes, correlation analysis to identify latent relationships among cost items, and regression models to predict cost trends. Time-series analysis was also employed to identify seasonal variations and long-term production trends (Asghari Araghi et al., 2024; Tran & Nguyen, 2024). For dynamic production scheduling and real-time resource allocation, a dynamic resource allocation optimization algorithm was designed based on deep neural networks and reinforcement learning. In this algorithm, production-flow data were initially received by data-collection nodes, after which a deep neural network with a number of hidden layers proportional to the scale and complexity of the data was trained. The loss function was defined on the basis of mean squared error, as presented in Equation 2:

$$\mathcal{L}_{\text{MSE}} = \frac{1}{n}\sum_{j=1}^{n}\left(y_j - \hat{y}_j\right)^2, \qquad (2)$$

where $y_j$is the observed value, $\hat{y}_j$is the predicted value, and $n$is the number of observations.

The reinforcement-learning reward function was defined as shown in Equation 3:

$$r_t = -(\alpha C_t + \beta D_t + \gamma W_t + \delta E_t), \qquad (3)$$

where $r_t$denotes the reward received at time t; $C_t$represents production cost; $D_t$denotes equipment downtime; $W_t$represents resource waste; and $E_t$denotes the deviation between actual and scheduled production. The coefficients α, β, γ, and δrepresent the relative importance assigned to each performance component.

If overfitting occurred, the network architecture was adjusted and the model was retrained. Monte Carlo simulation was ultimately used to predict data flows, while reinforcement learning was employed to optimize the allocation of network resources (Guo et al., 2023; Liang et al., 2020). Indirect costs were allocated to different activities on the basis of appropriate cost drivers. First, the principal production activities were identified. Subsequently, the activity rate was calculated by dividing the total cost of each activity by the volume of its corresponding cost driver. Finally, the cost of each product was estimated by summing its direct costs and its allocated share of indirect costs (Bakhrano, 2023; Nguyen, 2023).

The activity rate was calculated as follows:

$$AR_k = \frac{AC_k}{CDV_k}, \qquad (4)$$

where AR_krepresents the activity rate for activity k, AC_kdenotes the total cost of activity k, and CDV_krepresents the total volume of the relevant cost driver.

The cost assigned to each product was calculated as:

$$TC_i = DC_i + \sum_{k=1}^{K} (AR_k \times CDU_{ik}), \qquad (5)$$

where TC_i denotes the total cost of product i, DC_i represents its direct costs, and CDU_{ik} denotes the number of cost-driver units consumed by product i in relation to activity k.

The final research model was designed by integrating the four aforementioned technologies and using the Internet of Things to enable automated data collection. The model was implemented through the following stages:

1. **Automated data collection:** Sensors and Internet of Things equipment were installed on production lines to collect real-time data on production speed, equipment status, and material consumption.
2. **Real-time analysis using artificial intelligence:** Artificial intelligence was used to automatically identify anomalies and provide managers with warnings through a control dashboard.
3. **Optimization through mixed-integer linear programming:** The model determined the optimal configuration of production lines and the most efficient allocation of resources during each time interval.
4. **Cost forecasting through data mining:** Cost and demand trends were predicted to enable proactive adjustments to production schedules.
5. **Cost allocation through activity-based costing:** The actual cost of each product was calculated on the basis of the activities performed and the resources consumed.

The integrated model minimized the level of human intervention and enabled real-time managerial decision-making.

To assess the performance of the proposed model in comparison with the traditional method, three principal indicators were defined.

The cost accounting accuracy indicator was calculated as follows:

$$GACC = \frac{NCCA}{TNCA} \times 100, \qquad (6)$$

where $NCCA$ represents the number or value of costs correctly calculated following the implementation of the new model, and $TNCA$ represents the total number or value of accounted costs (Medina, 2023).

The cost-control efficiency indicator was calculated as:

$$CCE = \frac{CCCASU - CCCBSU}{CCCBSU} \times 100, \qquad (7)$$

where $CCCASU$ represents cost-control capability after the application of the new system, and $CCCBSU$ represents cost-control capability before the application of the new system (Abnan et al., 2023).

The overall management efficiency indicator was calculated as:

$$OME = \frac{MESU - MEBSU}{MEBSU} \times 100, \qquad (8)$$

where $MESU$ represents the level of managerial efficiency after the implementation of the new system, and $MEBSU$ represents the level of managerial efficiency before its implementation (Qatawneh et al., 2023).

The collected data were initially summarized using descriptive statistics, including the mean and standard deviation. The mixed-integer linear programming model was subsequently solved using optimization software, such as the General Algebraic Modeling System or the PuLP library in Python. The deep-learning algorithm was implemented in the TensorFlow environment. Data mining and time-series analyses were conducted using Python libraries, including scikit-learn, pandas, and statsmodels. Finally, the values of the three indicators—cost accounting accuracy, cost-control efficiency, and overall management efficiency—were calculated before and after the implementation of the proposed model. The preimplementation and postimplementation values were compared using a paired-samples *t* test at a 95% confidence level to determine whether the observed improvements were statistically significant.

3. Findings and Results

The findings are reported according to the three principal technological applications examined in the study: mixed-integer linear programming for resource allocation and cost reassignment, big data analytics for improving cost-measurement and forecasting accuracy, and artificial intelligence for production scheduling and predictive maintenance. The results are presented for the Kufa Cement Plant, Najaf Cement Plant, Baghdad Soft Drinks Company, and Iraqi Carpet Company over the 2020–2024 period.

The results associated with the first hypothesis indicated that applying the mixed-integer linear programming model to recalculate industrial costs at the Kufa Cement Plant produced substantial differences between the costs calculated using the traditional method and those obtained after optimization. The initial monthly analysis for January–May 2020 incorporated fuel and lubricant costs, raw-material costs, packaging costs, wages and salaries, total direct costs, production time, cement production, clinker production, and the unit cost before and after implementation of the optimization model.

Table 1 .Monthly Direct Costs and Initial Unit-Cost Results at the Kufa Cement Plant, January–May 2020

Month	Fuel and lubricants (IQD)	Raw materials (IQD)	Packaging (IQD)	Wages and salaries (IQD)	Total direct costs (IQD)	Production time	Cement production (tons)	Clinker production (tons)	Cost before MILP (IQD/ton)	Cost after MILP (IQD/ton)	Reported unit-cost difference (%)
January 2020	632,413,349	277,687,256	117,426,488	1,696,826,267	2,724,353,360	60	37,236	32,488	63,349	37,875	37.42
February 2020	758,896,019	333,224,707	140,911,785	1,766,241,887	2,999,274,398	65	44,683	38,985	54,590	39,898	42.23
March 2020	1,011,861,359	444,299,610	187,882,380	1,905,073,127	3,549,116,476	70	59,578	51,980	43,757	42,311	49.16
April 2020	1,138,344,029	499,837,061	211,367,678	1,974,489,746	3,824,037,514	50	67,025	58,478	41,598	41,664	50.04
May 2020	1,264,826,699	555,374,512	234,852,976	2,043,904,366	4,098,958,553	60	74,472	64,975	40,900	40,117	49.52

The monthly results demonstrate that the observed differences were not merely hypothetical reductions in reported costs. Rather, they reflected a more accurate allocation of indirect costs after the costs associated with clinker production were identified and assigned to the activities that generated them. Under the traditional costing method, a large proportion of indirect production costs was charged entirely to finished cement. The optimization model instead separated the costs attributable to clinker from those directly associated with the final cement-production stage.

The annual findings further indicated that the recalculated cost per ton was lower than the traditionally calculated cost in every year from 2020 to 2024. In 2020, the traditional cost was IQD 85,057 per ton, whereas the optimized cost was IQD 67,175, representing a difference of IQD 17,883 or 21.02%. The corresponding reduction was 14.47% in 2021, 21.39% in 2022, 20.52% in 2023, and 10.15% in 2024.

The annual variation indicates a persistent methodological gap between the traditional and optimized approaches. The gap demonstrates that reallocating indirect costs on the basis of actual resource consumption produced a more accurate estimate of industrial costs. As the financial importance of energy consumption, maintenance, and depreciation increased, charging all such costs to finished cement became increasingly misleading because these cost elements were predominantly generated during clinker production. The MILP model corrected this distortion by assigning costs according to their actual sources and operational drivers.

The findings for the Najaf Cement Plant similarly revealed meaningful differences between the traditional cost calculation and the recalculated cost obtained after implementing the mixed-integer linear programming model. In every year examined, the cost per ton determined through the traditional method exceeded the corresponding optimized cost.

The difference arose primarily because the traditional method aggregated indirect costs and allocated them to finished cement without adequately considering the relationship between cost-generating resources and the different production stages. This limitation was especially consequential for clinker production, which accounted for a substantial proportion of energy consumption, equipment maintenance, and depreciation.

Under the MILP model, indirect costs were redistributed between clinker and cement according to more realistic cost drivers, including actual production volume, patterns of resource consumption, and the operational constraints of the plant. Consequently, the portion of indirect costs previously and inaccurately assigned to finished cement was removed, resulting in a more precise calculation of the cost per ton.

The cost difference was relatively moderate during the earlier years but became particularly evident in 2023 and 2024. This pattern may be associated with greater complexity in the plant's cost structure and changes in its production pattern. These developments exposed the limitations of the traditional costing system and demonstrated the ability of the optimization model to correct cost-allocation distortions.

The first-hypothesis findings for the Baghdad Soft Drinks Company also showed considerable differences between conventional cost calculations and the results obtained after applying mixed-integer linear programming. The optimized results were consistently lower than the traditional unit cost, indicating improved cost-measurement accuracy rather than an arbitrary or purely nominal cost reduction.

Under the traditional system, current and indirect costs were aggregated and assigned to production without a sufficiently clear distinction between manufacturing costs and costs of an administrative or marketing nature. This method resulted in an overstatement of product costs, particularly in a multi-activity processing industry in which production, packaging, marketing, distribution, and administration coexist.

The MILP application allowed indirect costs to be reassigned according to more realistic cost drivers. Costs strongly associated with manufacturing, including production services, utilities, and depreciation, were assigned to production units. In contrast, administrative and marketing costs were excluded from product costs or allocated a smaller share because they were treated as period costs rather than costs directly generated by manufacturing activities.

The reported percentage difference between the traditional and optimized costs ranged from 4.08% to 14.59% over the five-year period. This relatively persistent pattern shows that the traditional method contained a continuous cost-allocation distortion that was corrected by the MILP model.

At the Iraqi Carpet Company, the results showed the largest differences between the traditional cost calculation and the MILP-based calculation. The analysis integrated actual production data, downtime records, and direct and indirect cost information for 2020–2024.

The optimized unit cost was lower than the traditional unit cost in every year, with reported differences ranging from 41.24% to 88.46%. This result should not be interpreted solely as an accounting reduction in costs. Instead, it indicates a fundamental correction in cost measurement. The traditional method assigned a comparatively large proportion of nonproduction and weakly production-related costs to the products. The MILP model reassigned indirect costs according to the resources consumed during the carpet-manufacturing process and reduced the inclusion of administrative and marketing costs in product cost.

The recalculated unit cost therefore provided a more accurate representation of the actual resources consumed. This improvement enhanced the quality of cost information available for pricing, production planning, resource allocation, and performance evaluation. The stability of the overall finding across the five-year period further suggests that the limitations of the traditional method were structural rather than temporary.

Table 2. **Annual Unit Costs Before and After MILP Implementation in the Four Industrial Units, 2020–2024**

Industrial unit	Year	Cement, clinker, or relevant output	Cost before MILP (IQD/unit)	Cost after MILP (IQD/unit)	Cost difference (IQD/unit)	Reduction (%)
Kufa Cement Plant	2020	Cement: 744,723 tons; clinker: 649,754 tons	85,057	67,175	17,883	21.02
Kufa Cement Plant	2021	Cement: 657,310 tons; clinker: 632,506 tons	106,420	91,018	15,402	14.47
Kufa Cement Plant	2022	Cement: 729,310 tons; clinker: 650,378 tons	101,262	79,606	21,656	21.39
Kufa Cement Plant	2023	Cement: 834,620 tons; clinker: 733,038 tons	103,664	82,395	21,270	20.52
Kufa Cement Plant	2024	Cement: 680,737 tons; clinker: 663,624 tons	127,626	114,673	12,954	10.15
Najaf Cement Plant	2020	Cement: 132,647 tons; clinker: 121,896 tons	120,081	91,221	28,859	24.03
Najaf Cement Plant	2021	Cement: 107,849 tons; clinker: 120,851 tons	143,040	116,123	26,917	18.82
Najaf Cement Plant	2022	Cement: 101,123 tons; clinker: 69,420 tons	163,448	124,177	39,271	24.03
Najaf Cement Plant	2023	Cement: 59,320 tons; clinker: 60,532 tons	219,492	188,388	31,103	14.17
Najaf Cement Plant	2024	Cement: 113,788 tons; clinker: 15,639 tons	150,888	124,011	26,877	17.81
Baghdad Soft Drinks Company	2020	One package	3,880	3,602	278	7.16
Baghdad Soft Drinks Company	2021	One package	4,588	3,919	669	14.59
Baghdad Soft Drinks Company	2022	One package	5,821	5,371	450	7.74
Baghdad Soft Drinks Company	2023	One package	5,158	4,948	210	4.08
Baghdad Soft Drinks Company	2024	One package	4,778	4,357	421	8.81

Iraqi Carpet Company	2020	One production unit	174,597	99,827	74,771	42.82
Iraqi Carpet Company	2021	One production unit	1,504,273	173,622	1,330,651	88.46
Iraqi Carpet Company	2022	One production unit	766,535	95,829	670,706	87.50
Iraqi Carpet Company	2023	One production unit	883,475	286,218	597,257	67.60
Iraqi Carpet Company	2024	One production unit	289,370	170,027	119,342	41.24

The comparative results show that the impact of MILP differed considerably across industrial contexts. At the Kufa Cement Plant, annual cost reductions ranged from 10.15% to 21.39%. At the Najaf Cement Plant, they ranged from 14.17% to 24.03%. The Baghdad Soft Drinks Company recorded smaller but persistent reductions ranging from 4.08% to 14.59%. The Iraqi Carpet Company had the largest reductions, ranging from 41.24% to 88.46%.

Table 3. Comparative Percentage Reduction in Unit Costs After MILP Implementation

Year	Kufa Cement Plant	Najaf Cement Plant	Baghdad Soft Drinks Company	Iraqi Carpet Company
2020	21.02%	24.03%	7.16%	42.82%
2021	14.47%	18.82%	14.59%	88.46%
2022	21.39%	24.03%	7.74%	87.50%
2023	20.52%	14.17%	4.08%	67.60%
2024	10.15%	17.81%	8.81%	41.24%
Five-year mean	17.51%	19.77%	8.48%	65.52%

The Kufa Cement Plant exhibited comparatively stable cost reductions, although the magnitude fell to 10.15% in 2024. The Najaf Cement Plant showed greater annual fluctuation, with the highest reduction of 24.03% recorded in both 2020 and 2022 and the lowest reduction of 14.17% in 2023. These changes may reflect variations in production, resource consumption, maintenance requirements, and operational complexity.

The Baghdad Soft Drinks Company recorded substantially smaller cost reductions than the cement and carpet companies. The highest reduction occurred in 2021 at 14.59%, whereas the lowest occurred in 2023 at 4.08%. The relatively smaller reduction does not necessarily indicate a weaker model. Instead, it suggests that the company's traditional product-cost values contained less extreme allocation distortion than those of the other organizations.

The Iraqi Carpet Company consistently recorded the largest reductions. The reduction reached 88.46% in 2021 and remained above 67% in 2022 and 2023 before decreasing to 41.24% in 2024. These findings indicate that the traditional cost system assigned a particularly high proportion of indirect and nonproduction costs to carpet products. The MILP model substantially corrected this allocation.

Taken together, the results support the first hypothesis in all four industrial units. The mixed-integer linear programming model improved the assignment of indirect costs, aligned cost calculations with actual production activities, and generated more decision-relevant unit-cost information. Its impact was particularly strong in operations characterized by high indirect costs, multiple cost centers, complex production stages, or inaccurate traditional allocation bases.

The second hypothesis concerned the role of big data analytics in improving cost accounting accuracy, strengthening cost-control efficiency, reducing measurement and forecasting errors, supporting profitability growth, and enhancing operational management efficiency.

The practical analysis was based on monthly cost time series and a predictive analytical approach intended to reduce operational noise and identify hidden cost patterns. The process did not alter the underlying accounting records or impose an artificially simplified linear relationship. Instead, it sought to obtain a more stable and representative depiction of cost behavior over time.

Cost accounting accuracy was evaluated through the standard deviation, coefficient of variation, mean absolute error, and root mean squared error:

$$CV = \frac{\sigma}{\bar{x}},$$

$$MAE = \frac{1}{n}\sum_{i=1}^{n} | y_i - \hat{y}_i |,$$

and

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(y_i - \hat{y}_i)^2}.$$

A reduction in the standard deviation and coefficient of variation indicated greater unit-cost stability. Reductions in MAE and $RMSE$ indicated improvements in measurement and forecasting accuracy. Cost-control efficiency was assessed through the system's capacity to reduce fluctuations and absorb operational shocks. Profitability was examined through changes in unit cost, profit margins, and cumulative profit, whereas management efficiency was assessed indirectly through cost stability, reduced estimation error, and improved planning and decision-making capability.

The aggregated findings showed that big data analytics improved the cost-measurement indicators in all four industrial units, although the magnitude of the improvement varied substantially.

Table 4. Aggregated Big Data Validation Indicators for the Four Industrial Units, 2020–2024

Industrial unit	Indicator	Before big data analytics	After big data analytics	Relative change	Interpretation
Kufa Cement Plant	Standard deviation, σ	16,293	15,462	−5.11%	Reduced cost fluctuations
	Coefficient of variation, CV	0.1528	0.1458	−4.58%	Improved relative stability
	Mean absolute error, MAE	10,072	9,700	−3.70%	Improved measurement accuracy
	Root mean squared error, $RMSE$	13,183	12,846	−2.56%	Reduced forecasting error
	Cost–production R^2	0.334	0.298	−10.78%	More selective and realistic relationship
	Cumulative profit growth	—	—	+6.32%	Improved profitability
	Management efficiency	—	—	+33.26%	Improved control and decision-making
Najaf Cement Plant	Standard deviation, σ	14,924	14,564	−2.41%	Reduced cost fluctuations
	Coefficient of variation, CV	0.465	0.460	−1.08%	Improved relative stability
	Cost–production R^2	0.1301	0.1425	+9.50%	Improved explanatory relationship
	Mean absolute error, MAE	14,187	13,683	−3.55%	Improved measurement accuracy

	Root mean squared error, $RMSE$	14,799	14,442	−2.41%	Reduced measurement and forecasting error
	Cumulative profit growth	—	—	+0.3816%	Limited cumulative saving
	Management efficiency	—	—	+2.7923%	Limited overall improvement
Baghdad Soft Drinks Company	Standard deviation, σ	1.64	1.49	−9.15%	Reduced cost fluctuations
	Coefficient of variation, CV	0.203	0.185	−8.87%	Improved relative stability
	Cost–production R^2	0.412	0.401	−2.67%	More realistic relationship
	Mean absolute error, MAE	0.93	0.86	−7.53%	Reduced measurement error
	Root mean squared error, $RMSE$	1.21	1.12	−7.44%	Reduced forecasting error
	Cumulative profit growth	—	—	+21.92%	Financial saving from operational improvement
	Management efficiency	—	—	+35.73%	Strong decision-support improvement
Iraqi Carpet Company	Standard deviation, σ	146.16	26.01	−82.20%	Major reduction in direct unit-cost fluctuations
	Coefficient of variation, CV	0.6627	0.1206	−81.80%	Major improvement in relative stability
	Mean absolute error, MAE	133.88	18.02	−86.54%	Substantial improvement in measurement accuracy
	Root mean squared error, $RMSE$	144.93	25.79	−82.21%	Substantial reduction in forecasting error
	Cost–production R^2	0.218	0.204	−6.42%	More realistic operational relationship
	Cumulative profit growth	—	—	+63.86%	Material financial saving
	Management efficiency	—	—	+83.65%	Strong managerial decision support

For the Kufa Cement Plant, the validation indicators were calculated using the aggregated monthly data for 2020–2024 as a unified time series. This approach evaluated the overall effect of big data analytics without fragmenting the primary validation by year. It emphasized the model's capacity to address changes in time, operational conditions, and exceptional periods.

The standard deviation declined by 5.11%, from 16,293 to 15,462, while the coefficient of variation declined by 4.58%, from 0.1528 to 0.1458. These reductions indicate improved cost stability. The mean absolute error decreased by 3.70%, from 10,072 to 9,700, and the root mean squared error decreased by 2.56%, from 13,183 to 12,846. The reductions demonstrate that the reprocessed cost time series represented actual cost behavior more accurately.

The cost–production coefficient of determination declined from 0.334 to 0.298. This decline was interpreted as a more selective relationship after noisy, anomalous, or artificially inflated associations were removed. The objective of the analysis was not to maximize R^2mechanically, but to represent the genuine relationship between costs and production more realistically.

The improvement in unit-cost accuracy contributed to cumulative profit growth of 6.32%. This improvement could have arisen through the identification of unnecessary expenditures or through more accurate pricing and production decisions. Management efficiency increased by 33.26%, indicating that more stable and reliable cost information strengthened managers' ability to respond to operational and economic changes.

The annual results supported the aggregated findings. In 2020, the standard deviation fell from 62,580 to 41,131, MAE fell from 52,239 to 30,783, and $RMSE$ fell from 59,916 to 39,380. Profit growth was 0.45%, and management efficiency improved by 36.54%.

In 2021, the standard deviation decreased from 64,750 to 48,472, MAE decreased from 54,263 to 37,664, and $RMSE$ decreased from 61,994 to 46,408. Profit increased by 1.17%, and management efficiency increased by 26.96%.

In 2022, the standard deviation declined from 76,068 to 49,674, MAE declined from 63,584 to 37,235, and $RMSE$ declined from 72,829 to 47,559. Profit growth was 0.40%, and management efficiency increased by 36.95%.

In 2023, the standard deviation decreased from 69,743 to 42,998, MAE decreased from 58,442 to 31,114, and $RMSE$ decreased from 66,774 to 41,167. Although cumulative profit changed by −0.13%, management efficiency increased by 41.15%.

In 2024, the standard deviation declined from 88,676 to 68,579, MAE declined from 74,081 to 52,771, and $RMSE$ declined from 84,901 to 65,659. Profit increased by 1.43%, while management efficiency improved by 24.70%.

The same validation approach was applied to the Najaf Cement Plant. The findings demonstrated modest improvements in most aggregated indicators. The standard deviation decreased by 2.41%, the coefficient of variation decreased by 1.08%, MAE decreased by 3.55%, and $RMSE$ decreased by 2.41%. The cost–production R^2 increased by 9.50%, indicating a somewhat stronger explanatory relationship after processing.

Cumulative profit increased by approximately 0.38% during 2020–2024, and management efficiency increased by approximately 2.79%. These improvements were considerably smaller than those recorded at the Kufa Cement Plant.

The limited effect was attributable to operational variability, including substantial changes in production in certain years and instability in the relationship between unit cost and output. The annual data showed that the model did not improve every indicator in every year.

In 2020, the standard deviation decreased from 8,653 to 5,718, MAE decreased from 7,222 to 4,562, and $RMSE$ decreased from 8,284 to 5,474. Profit grew by 0.36%, and management efficiency improved by 34.89%.

In 2021, the standard deviation increased from 11,304 to 15,327, MAE increased from 9,403 to 11,141, and $RMSE$ increased from 10,823 to 14,674. Despite profit growth of 2.50%, management efficiency declined by 29.88%.

In 2022, the standard deviation decreased from 16,181 to 12,428, MAE decreased from 13,330 to 10,102, and $RMSE$ decreased from 15,492 to 11,899. Profit increased by 1.05%, and management efficiency improved by 23.53%.

In 2023, the standard deviation increased from 23,210 to 47,971, MAE increased from 19,374 to 32,318, and $RMSE$ increased from 22,222 to 45,928. Profit nevertheless increased by 3.98%, while management efficiency declined by 93.39%.

In 2024, the standard deviation increased from 17,065 to 19,063. However, MAE declined from 14,114 to 13,079, whereas $RMSE$ increased from 16,339 to 18,251. Profit declined by 2.15%, and management efficiency declined by 5.36%.

These mixed annual results indicate that big data analytics reduced part of the operational noise but remained constrained by the underlying data and cost structure. Accordingly, the second hypothesis was only partially supported at the Najaf Cement Plant.

Table 5. Annual Big Data Validation Results for the Kufa and Najaf Cement Plants

Plant	Year	$\boldsymbol{\sigma}$before	$\boldsymbol{\sigma}$after	$\boldsymbol{MAE}$before	$\boldsymbol{MAE}$after	$\boldsymbol{RMSE}$before	$\boldsymbol{RMSE}$after	Profit growth	Management efficiency
Kufa	2020	62,580	41,131	52,239	30,783	59,916	39,380	0.45%	36.54%
Kufa	2021	64,750	48,472	54,263	37,664	61,994	46,408	1.17%	26.96%

Kufa	2022	76,068	49,674	63,584	37,235	72,829	47,559	0.40%	36.95%
Kufa	2023	69,743	42,998	58,442	31,114	66,774	41,167	−0.13%	41.15%
Kufa	2024	88,676	68,579	74,081	52,771	84,901	65,659	1.43%	24.70%
Najaf	2020	8,653	5,718	7,222	4,562	8,284	5,474	0.36%	34.89%
Najaf	2021	11,304	15,327	9,403	11,141	10,823	14,674	2.50%	−29.88%
Najaf	2022	16,181	12,428	13,330	10,102	15,492	11,899	1.05%	23.53%
Najaf	2023	23,210	47,971	19,374	32,318	22,222	45,928	3.98%	−93.39%
Najaf	2024	17,065	19,063	14,114	13,079	16,339	18,251	−2.15%	−5.36%

The results for the Baghdad Soft Drinks Company demonstrated a systematic improvement in the accuracy and stability of cost information. The standard deviation decreased from 1.64 to 1.49, equivalent to a reduction of 9.15%. The coefficient of variation declined from 0.203 to 0.185, representing an 8.87% improvement in relative stability.

The cost–production R^2decreased slightly from 0.412 to 0.401. This change was interpreted positively because the analysis removed potentially exaggerated or artificial relationships associated with less accurate traditional measurements and generated a more realistic representation of the relationship between costs and activity levels.

The mean absolute error decreased by 7.53%, from 0.93 to 0.86, while the root mean squared error decreased by 7.44%, from 1.21 to 1.12. These changes demonstrate improved cost measurement and forecasting accuracy.

The economic results included cumulative profit growth of 21.92% and an improvement in management efficiency of 35.73%. Accordingly, the value of big data analytics was not limited to statistical improvements. It also supported managerial decisions and generated tangible financial benefits.

The annual results followed a consistent pattern. In 2020, σdeclined from 16,980 to 15,430, MAEdeclined from 14,210 to 13,140, and $RMSE$declined from 16,320 to 15,100. Profit grew by 2.25%, and management efficiency increased by 7.10%.

In 2021, σdeclined from 20,740 to 18,840, MAEdeclined from 17,060 to 15,780, and $RMSE$declined from 19,650 to 18,190. Profit increased by 3.95%, and management efficiency increased by 8.60%.

In 2022, σdeclined from 16,520 to 15,010, MAEdeclined from 13,820 to 12,780, and $RMSE$declined from 15,780 to 14,610. Profit increased by 4.30%, and management efficiency improved by 8.10%.

In 2023, which recorded the highest level of cost variability, σdecreased from 23,980 to 21,790, MAEdecreased from 20,140 to 18,620, and $RMSE$decreased from 23,150 to 21,430. Profit increased by 6.80%, and management efficiency improved by 6.90%.

In 2024, σdeclined from 21,630 to 19,650, MAEdeclined from 18,320 to 16,940, and $RMSE$declined from 20,940 to 19,380. Profit increased by 4.62%, and management efficiency improved by 5.03%.

The analysis of the Iraqi Carpet Company focused on direct cost components because its labor-intensive production system was characterized by variability in raw materials, operational efficiency, and output levels.

The standard deviation decreased from 146.16 to 26.01, representing a reduction of 82.20%. The coefficient of variation decreased from 0.6627 to 0.1206, representing an improvement of 81.80%. These results indicate a substantial increase in unit-cost stability.

The mean absolute error declined from 133.88 to 18.02, equivalent to a reduction of 86.54%. The root mean squared error declined from 144.93 to 25.79, representing a reduction of 82.21%. These changes demonstrate a major improvement in the system's ability to estimate actual costs and forecast future costs while reducing the influence of extreme deviations.

The cost–production R^2 declined slightly from 0.218 to 0.204. Although the numerical change was negative, it indicated that the model produced a less exaggerated and more operationally realistic relationship between costs and production. Big data processing therefore reduced the risk of interpreting spurious correlations as genuine production relationships.

Cumulative profit increased by 63.86%, while management efficiency improved by 83.65%. These results show that improved cost accuracy was reflected in lower waste, better resource utilization, and stronger operational and strategic decision-making.

The annual analysis confirmed that the improvements were sustained. In 2020, σ decreased from 151.4 to 31.2, a reduction of 79.40%; MAE declined from 138.7 to 22.9, a reduction of 83.49%; and $RMSE$ declined from 149.9 to 30.5, a reduction of 79.66%. Profit increased by 12.4%.

In 2021, σ decreased from 158.2 to 28.6, MAE decreased from 145.3 to 19.8, and $RMSE$ decreased from 156.7 to 27.9. The corresponding reductions were 81.92%, 86.38%, and 82.19%, while profit increased by 18.6%.

In 2022, σ declined by 82.54%, from 142.6 to 24.9; MAE declined by 86.78%, from 130.1 to 17.2; and $RMSE$ declined by 82.88%, from 140.8 to 24.1. Profit increased by 10.3%.

In 2023, σ declined by 82.90%, MAE declined by 86.94%, and $RMSE$ declined by 83.14%. Profit increased by 9.7%.

In 2024, the reduction in σ reached 84.55%, the reduction in MAE reached 88.67%, and the reduction in $RMSE$ reached 85.22%. Profit increased by 12.9%.

Table 6. Annual Big Data Validation Results for the Baghdad Soft Drinks Company and Iraqi Carpet Company

Company	Year	$\boldsymbol{\sigma}$before	$\boldsymbol{\sigma}$after	$\boldsymbol{MAE}$before	$\boldsymbol{MAE}$after	$\boldsymbol{RMSE}$before	$\boldsymbol{RMSE}$after	Profit growth
Baghdad Soft Drinks	2020	16,980	15,430	14,210	13,140	16,320	15,100	2.25%
Baghdad Soft Drinks	2021	20,740	18,840	17,060	15,780	19,650	18,190	3.95%
Baghdad Soft Drinks	2022	16,520	15,010	13,820	12,780	15,780	14,610	4.30%
Baghdad Soft Drinks	2023	23,980	21,790	20,140	18,620	23,150	21,430	6.80%
Baghdad Soft Drinks	2024	21,630	19,650	18,320	16,940	20,940	19,380	4.62%
Iraqi Carpet	2020	151.4	31.2	138.7	22.9	149.9	30.5	12.4%
Iraqi Carpet	2021	158.2	28.6	145.3	19.8	156.7	27.9	18.6%
Iraqi Carpet	2022	142.6	24.9	130.1	17.2	140.8	24.1	10.3%
Iraqi Carpet	2023	136.9	23.4	125.6	16.4	135.2	22.8	9.7%
Iraqi Carpet	2024	141.7	21.9	129.8	14.7	142.1	21.0	12.9%

Overall, the big data findings demonstrate that the technology improved cost-calculation accuracy across all four organizations by reducing unit-cost variability and decreasing measurement and forecasting errors. Its principal value was not necessarily the direct reduction of the accounting mean cost. Instead, its contribution was to improve the quality, stability, and reliability of cost information used in managerial decisions.

The second hypothesis was strongly supported at the Kufa Cement Plant, Baghdad Soft Drinks Company, and Iraqi Carpet Company. It was partially supported at the Najaf Cement Plant because the aggregated indicators showed modest improvement, while several annual indicators deteriorated during years of substantial operational instability.

The third hypothesis examined the accounting and operational consequences of applying artificial intelligence rather than the technical development of an independent deep-learning or reinforcement-learning software system. The practical applications included predictive models, analysis of downtime patterns, production-schedule optimization, and predictive maintenance.

The effects were evaluated according to four dimensions: improvement in cost-calculation accuracy, reduction in unplanned downtime, improvement in production scheduling, and improvement in the usefulness of accounting information for managerial maintenance and scheduling decisions.

At the Kufa Cement Plant, artificial intelligence was applied to improve scheduling and predictive maintenance. Its impact was measured through changes in unplanned downtime and the resulting changes in unit cost.

In 2020, the cost per ton decreased from IQD 85,057 to IQD 84,814, a reduction of IQD 243 or 0.29%, while unplanned downtime decreased by 4.17%. In 2021, the cost per ton decreased by IQD 210 or 0.20%, and downtime decreased by 4.50%. In 2022, the cost declined by IQD 192 or 0.19%, accompanied by a 4.50% reduction in downtime. In 2023, the cost decreased by IQD 279 or 0.27%, and downtime decreased by 6.98%.

No cost or downtime reduction was recorded in 2024. The lack of improvement did not necessarily represent model failure. Rather, the observed downtime did not exceed the threshold for abnormally high downtime targeted by the predictive-maintenance mechanism. Consequently, no substantial downtime-related waste was identified for artificial intelligence to reduce.

At the Najaf Cement Plant, artificial intelligence produced a larger operational effect, particularly in years characterized by greater instability. In 2020, cost per ton declined by 6.00%, and downtime declined by 9.21%. The corresponding improvements were 6.40% and 9.87% in 2021, 9.30% and 11.14% in 2022, 10.60% and 13.36% in 2023, and 5.70% and 7.00% in 2024.

Although the percentage cost reductions were moderate relative to the MILP effects, they were operationally realistic for a capital-intensive industry. The pattern indicates that artificial intelligence improved scheduling and maintenance performance and that its economic value increased when the plant experienced higher levels of operational disruption.

At the Baghdad Soft Drinks Company, artificial intelligence improved production scheduling and reduced operational instability. The cost per package decreased by 1.143% in 2020, 0.79% in 2021, 0.57% in 2022, 1.05% in 2023, and 0.75% in 2024.

These reductions were small but consistent. They indicate that, in the food and beverage industry, the primary value of artificial intelligence was the stabilization of scheduling and improvement of managerial decisions rather than a dramatic direct reduction in product cost. Actual downtime data were unavailable for this company; therefore, the effect was evaluated primarily through unit-cost changes and production-scheduling stability.

At the Iraqi Carpet Company, artificial intelligence reduced unplanned downtime and improved operational stability, although the resulting unit-cost reductions remained comparatively small. The unit cost declined by 5.66% in 2020, 0.93% in 2021, 1.16% in 2022, 0.14% in 2023, and 2.17% in 2024. The corresponding reported reductions associated with downtime or operational instability were 5.38%, 2.49%, 7.54%, 0.98%, and 5.36%.

Because carpet production is labor-intensive, improved scheduling and operational continuity may reveal actual costs more accurately rather than merely reducing them. Costs that had previously remained concealed or distorted during downtime periods became more accurately represented when production continuity improved. Consequently, the primary benefit of artificial intelligence in this company was improved cost-measurement accuracy and managerial decision support.

Table 7. Annual Results of Artificial Intelligence Implementation in the Four Industrial Units

Industrial unit	Year	Unit cost before AI (IQD)	Unit cost after AI (IQD)	Cost reduction (IQD)	Cost reduction (%)	Downtime or instability reduction
Kufa Cement Plant	2020	85,057	84,814	243	0.29%	4.17%
Kufa Cement Plant	2021	106,420	106,210	210	0.20%	4.50%

Kufa Cement Plant	2022	101,262	101,070	192	0.19%	4.50%
Kufa Cement Plant	2023	103,664	103,385	279	0.27%	6.98%
Kufa Cement Plant	2024	127,626	127,626	0	0.00%	0.00%
Najaf Cement Plant	2020	120,081	112,876	7,205	6.00%	9.21%
Najaf Cement Plant	2021	143,040	133,885	9,155	6.40%	9.87%
Najaf Cement Plant	2022	163,448	148,248	15,200	9.30%	11.14%
Najaf Cement Plant	2023	219,492	196,226	23,266	10.60%	13.36%
Najaf Cement Plant	2024	150,888	142,288	8,600	5.70%	7.00%
Baghdad Soft Drinks Company	2020	3,880	3,836	44	1.143%	Not available
Baghdad Soft Drinks Company	2021	4,588	4,552	36	0.79%	Not available
Baghdad Soft Drinks Company	2022	5,821	5,788	33	0.57%	Not available
Baghdad Soft Drinks Company	2023	5,158	5,104	54	1.05%	Not available
Baghdad Soft Drinks Company	2024	4,778	4,742	36	0.75%	Not available
Iraqi Carpet Company	2020	174,597	164,715	9,882	5.66%	5.38%
Iraqi Carpet Company	2021	1,504,273	1,490,284	13,989	0.93%	2.49%
Iraqi Carpet Company	2022	766,535	757,643	8,892	1.16%	7.54%
Iraqi Carpet Company	2023	883,475	882,238	1,237	0.14%	0.98%
Iraqi Carpet Company	2024	289,370	283,091	6,279	2.17%	5.36%

The annual data indicate that the mean unit-cost reduction attributable to artificial intelligence was approximately 0.19% at the Kufa Cement Plant, 7.60% at the Najaf Cement Plant, 0.86% at the Baghdad Soft Drinks Company, and 2.01% at the Iraqi Carpet Company.

The aggregated values reported in the original operational summaries were expressed using different unit scales from the full annual accounting records. Those summaries reported average costs of IQD 104,806 and IQD 104,621 per ton at Kufa, IQD 32,901 and IQD 32,496 per ton at Najaf, IQD 8.79 and IQD 8.72 per package at Baghdad, and IQD 507.70 and IQD 503.57 per unit at the Iraqi Carpet Company. Because these aggregate figures were generated from plant-specific normalized accounting series, they should be interpreted within their respective operational scales rather than compared directly with the nominal annual values in Table 7.

Table 8. Aggregated Interpretation of Artificial Intelligence Outcomes

Industrial unit	Mean cost reduction based on annual percentages	Reported mean downtime or instability reduction	Principal accounting and operational interpretation
Kufa Cement Plant	0.19%	4.83% in the reported operational summary	Limited but realistic cost reduction resulting from fewer abnormal stoppages; no effect was recorded in 2024 because downtime remained below the predictive-maintenance intervention threshold.
Najaf Cement Plant	7.60%	6.32% in the reported operational summary	Strongest direct AI-related unit-cost improvement, reflecting the greater scope for predictive maintenance and schedule correction in years of high operational instability.
Baghdad Soft Drinks Company	0.86%	Not available	Consistent improvement attributable primarily to production-schedule stability; actual downtime observations were unavailable.
Iraqi Carpet Company	2.01%	4.75% in the reported operational summary	Modest cost reduction combined with improved cost visibility and measurement accuracy in a labor-intensive production environment.

Taken together, the third-hypothesis results indicate that artificial intelligence improved operational efficiency and reduced unplanned downtime or production instability across the studied units. However, its effect on unit cost differed according to industrial characteristics.

In capital-intensive and equipment-dependent operations, particularly the Najaf Cement Plant, predictive maintenance and production-scheduling improvements generated more visible unit-cost reductions. At the Kufa Cement Plant, the cost impact was smaller because the level of abnormal downtime was lower, especially in 2024. At the Baghdad Soft Drinks Company, the main benefit was schedule stability. At the Iraqi Carpet Company, artificial intelligence primarily improved the accuracy with which actual resource consumption and downtime-related costs were represented.

The third hypothesis was therefore supported. Artificial intelligence contributed to greater cost-accounting accuracy, improved production scheduling, reduced unplanned downtime where such downtime was material, and strengthened managerial decisions related to maintenance and operational planning.

The three technologies did not affect all companies in the same manner. Mixed-integer linear programming had its greatest impact where traditional indirect-cost allocations were substantially distorted. Its mean unit-cost reduction was 17.51% at Kufa Cement, 19.77% at Najaf Cement, 8.48% at Baghdad Soft Drinks, and 65.52% at Iraqi Carpet.

Big data analytics had its greatest effect on cost stability and measurement accuracy. The reduction in MAE was 3.70% at Kufa Cement, 3.55% at Najaf Cement, 7.53% at Baghdad Soft Drinks, and 86.54% at Iraqi Carpet. The exceptionally large improvement at the Iraqi Carpet Company reflects the initial instability of its direct-cost data and the value of identifying outliers and hidden temporal patterns.

Artificial intelligence generated the largest direct unit-cost reduction at the Najaf Cement Plant, where the five-year mean reduction was 7.60%. Its effects were smaller at the Kufa Cement Plant, Baghdad Soft Drinks Company, and Iraqi Carpet Company because its primary contribution in those organizations was the stabilization of operations and improvement of cost visibility rather than the achievement of large direct accounting savings.

Overall, the findings demonstrate that the systematic integration of MILP, big data analytics, and artificial intelligence enhanced resource allocation, improved cost-accounting accuracy, reduced measurement and forecasting errors, supported more effective production scheduling, and strengthened managerial decision-making. The results support all three hypotheses, although the second hypothesis received only partial support at the Najaf Cement Plant because of inconsistent annual effects under conditions of severe operational variability.

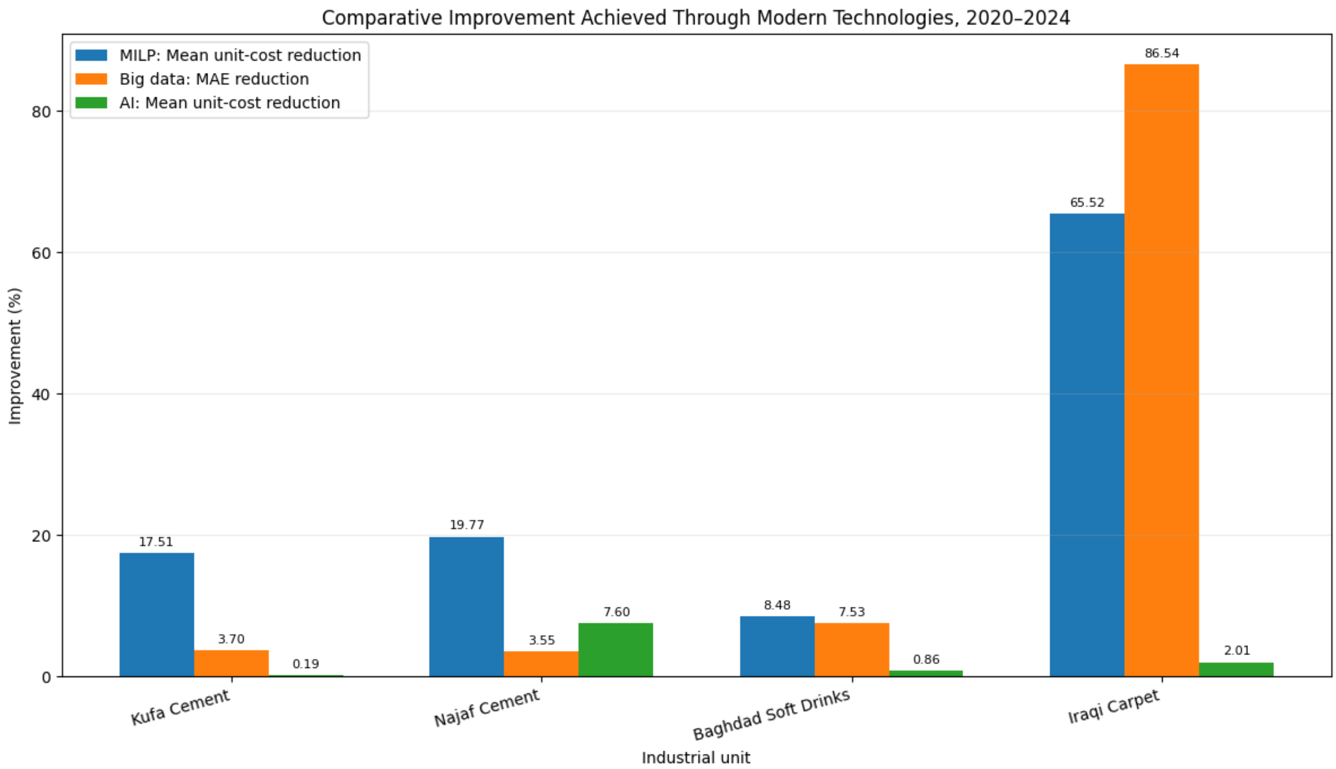

Figure 1. Comparative Improvements Achieved Through Mixed-Integer Linear Programming, Big Data Analytics, and Artificial Intelligence, 2020–2024

4. Discussion and Conclusion

The present study examined the contribution of mixed-integer linear programming, big data analytics, and artificial intelligence to resource allocation, cost-accounting accuracy, production scheduling, and managerial efficiency in four Iraqi industrial units during 2020–2024. The findings collectively support the proposition that the value of modern technologies extends beyond the mechanical reduction of reported costs. Their more fundamental contribution lies in improving the informational quality of cost systems by connecting accounting measurements to actual production activities, resource-consumption patterns, operational constraints, and equipment conditions. This interpretation is consistent with the informationalism perspective adopted in the study, according to which organizational efficiency depends increasingly on the capacity to collect, process, interpret, and apply large volumes of timely information. Reliable cost information reduces information asymmetry, strengthens monitoring, and constrains inefficient managerial discretion, which accords with the agency-theoretical argument that information and control systems are essential for reducing conflicts arising from the separation of ownership and management [2]. The findings also support the broader view that accounting information plays an important role in governance, contracting, and resource allocation when it accurately represents the organization's underlying economic activities [37].

The first major finding was that mixed-integer linear programming reduced the recalculated unit cost in all four industrial units, although the magnitude differed substantially across companies. The average reduction was approximately 17.51% at the Kufa Cement Plant, 19.77% at the Najaf Cement Plant, 8.48% at the Baghdad Soft Drinks Company, and 65.52% at the Iraqi Carpet Company. The most important interpretation of these reductions is not that the model artificially lowered costs, but that it corrected distortions produced by traditional cost-allocation practices. In the cement plants, the conventional method assigned a disproportionately large share of indirect expenses to finished cement without adequately separating the resources consumed during clinker production. The optimization model redistributed energy, maintenance, depreciation, and other indirect costs according to production volume, resource usage, and operational constraints. Consequently, the resulting unit costs were more closely aligned with the actual sources of cost generation. This outcome is conceptually consistent with evidence that accounting quality deteriorates when estimation procedures do not accurately represent underlying economic processes [11]. It also accords with the argument that measurement models must separate genuine economic effects from estimation error and inappropriate model specification [12].

At the Kufa Cement Plant, annual unit-cost reductions ranged from 10.15% to 21.39%, while those at the Najaf Cement Plant ranged from 14.17% to 24.03%. The persistence of these differences across five years suggests that the traditional allocation problem was structural rather than temporary. In both plants, clinker production accounted for a substantial proportion of energy use, equipment deterioration, and maintenance requirements. Assigning these costs entirely or predominantly to finished cement overstated the cost of the final production stage and obscured the economic performance of intermediate production activities. The MILP model improved cost attribution by treating production stages and resource constraints explicitly. This result parallels the accounting literature's emphasis on distinguishing normal economic components from discretionary or incorrectly measured components when evaluating reporting quality [9, 10]. Just as accrual models seek to isolate abnormal accounting adjustments, the optimization framework used in this study separated genuine production costs from costs that had been assigned through overly aggregated conventional procedures.

The effect of MILP was smaller but still consistent at the Baghdad Soft Drinks Company, where annual reductions ranged from 4.08% to 14.59%. The relatively modest magnitude can be explained by the company's different cost structure. Unlike cement manufacturing, soft-drink production combines manufacturing, packaging, distribution, marketing, and administrative activities. The traditional system incorporated some period costs into product costs, thereby overstating the cost per package. The optimization model improved classification by assigning production-related utilities, depreciation, and service costs to manufacturing while reducing the inclusion of administrative and marketing expenditures that were not directly generated by production. This result reinforces the idea that the usefulness of accounting information depends on classification accuracy and its ability to reflect the economic substance of transactions and activities. Financial information loses relevance when accounting categories fail to represent the actual structure of organizational value creation [1]. The more moderate improvement at the Baghdad company therefore does not indicate weak model performance; rather, it reflects a smaller initial allocation distortion than that observed in the cement and carpet companies.

The largest MILP effect occurred at the Iraqi Carpet Company, where annual cost differences ranged from 41.24% to 88.46%. Such substantial reductions suggest that the traditional costing method had allocated a large amount of nonproduction or weakly production-related expenditure to individual carpet units. The labor-intensive nature of the industry, variation in raw-material combinations, fluctuating output, and the coexistence of direct labor with administrative and marketing activities may have made conventional overhead allocation particularly inaccurate. Through the integration of production volumes, resource consumption, downtime, and cost constraints, the model generated a substantially more representative unit cost. This finding is consistent with the general accounting principle that higher-quality information reduces the risk of distorted performance assessments and inappropriate economic decisions [7]. It also supports the valuation-oriented conclusion that accounting numbers are useful only to the extent that they faithfully capture the economic resources and outcomes to which they refer [5].

The second major finding was that big data analytics improved cost stability and reduced measurement and forecasting errors in all companies, although the results were heterogeneous. At the Kufa Cement Plant, the standard deviation decreased by 5.11%, the coefficient of variation by 4.58%, the mean absolute error by 3.70%, and the root mean squared error by 2.56%. These improvements were accompanied by cumulative profit growth of 6.32% and a 33.26% improvement in management efficiency. The findings indicate that processing monthly cost series, detecting anomalous values, and extracting temporal patterns produced more stable and reliable cost information. This interpretation is compatible with the literature on accrual quality, which identifies estimation error as a major source of reduced accounting reliability [11]. It is also consistent with the view that earnings and accounting measurements become more decision-useful when they are persistent, predictable, and less contaminated by noise [7]. The improvement in managerial efficiency can therefore be explained by the increased ability of managers to distinguish persistent cost trends from short-term disturbances.

The Najaf Cement Plant showed smaller aggregated improvements: the standard deviation declined by 2.41%, the coefficient of variation by 1.08%, the mean absolute error by 3.55%, and the root mean squared error by 2.41%. Cumulative profit and management-efficiency gains were also limited. Moreover, annual results were inconsistent, with deterioration in several indicators during 2021, 2023, and 2024. This finding demonstrates that big data technologies do not automatically produce uniform benefits. Their effectiveness depends on data quality, production stability, the severity of structural changes, and the adequacy of the variables included in the analytical model. In years characterized by sharp production changes or unusual operating conditions, historical patterns may have had limited predictive value. This result aligns with warnings that accounting models are sensitive to research design, economic conditions, and measurement assumptions [12]. It also reflects the conclusion that apparently persistent accounting patterns can be influenced by underlying business dynamics and should not automatically be interpreted as evidence of improved quality [14]. Accordingly, the second hypothesis was only partially confirmed at the Najaf Cement Plant.

At the Baghdad Soft Drinks Company, big data analytics reduced the standard deviation by 9.15%, the coefficient of variation by 8.87%, the mean absolute error by 7.53%, and the root mean squared error by 7.44%. These statistical improvements were accompanied by cumulative profit growth of 21.92% and a management-efficiency increase of 35.73%. The consistent annual reductions in variability and error suggest that the technology successfully identified production and cost patterns within a multi-activity manufacturing environment. By reducing the influence of short-term operational noise, the analytical system generated a more dependable basis for pricing, production planning, and resource allocation. This finding is compatible with evidence that stronger internal-control systems improve reporting quality by formalizing information flows and reducing errors in measurement and reporting [21]. It also supports governance research showing that monitoring effectiveness depends on access to relevant and reliable information [17, 18]. In the present context, big data analytics acted as a continuous internal-monitoring mechanism rather than merely as a forecasting tool.

The strongest big data results were observed at the Iraqi Carpet Company. The standard deviation decreased by 82.20%, the coefficient of variation by 81.80%, the mean absolute error by 86.54%, and the root mean squared error by 82.21%. Cumulative profit increased by 63.86%, while management efficiency improved by 83.65%. The exceptional magnitude of these changes indicates that the original cost data contained substantial volatility, anomalous values, or weakly structured relationships between cost and production. The analytical process improved data tracing, detected extreme observations, and generated a more stable representation of direct unit costs. This result resembles the role of high-quality auditing and governance in constraining inaccurate accounting outcomes. Higher audit quality has been associated with lower levels of opportunistic accounting adjustments because stronger verification improves the credibility of reported information [22]. Similarly, governance mechanisms can reduce earnings-management behavior by increasing oversight and limiting the opportunity to exploit weak information systems [19, 20]. Although the present study concerned industrial cost measurement rather than external earnings management, the underlying mechanism is comparable: more rigorous information processing reduces unexplained variation and improves the correspondence between reported numbers and actual economic activity.

The slight decline in the cost–production coefficient of determination in some companies should not be interpreted as evidence of analytical failure. At Kufa Cement, Baghdad Soft Drinks, and Iraqi Carpet, the post-implementation $R^2$was marginally lower than the preimplementation value. The purpose of big data processing was not to maximize statistical association but to remove spurious, exaggerated, or noise-driven relationships. A lower but more realistic coefficient can be preferable to a larger coefficient produced by distorted observations. This interpretation is consistent with the accounting literature's distinction between genuine informational content and mechanically smooth or persistent reporting patterns. Managers may create artificial regularity through accounting or real operating decisions, even though such regularity does not necessarily indicate higher reporting quality [13, 15]. Therefore, the reduction of artificial relationships can strengthen rather than weaken the representational faithfulness of cost information.

The third principal finding was that artificial intelligence improved production scheduling, predictive maintenance, and operational continuity, although the direct effect on unit costs varied across firms. At the Kufa Cement Plant, the average annual unit-cost reduction was approximately 0.19%, while downtime decreased in the years in which abnormal stoppages occurred. No reduction was recorded in 2024 because downtime did not exceed the threshold targeted by the predictive-maintenance mechanism. This finding demonstrates that the economic value of artificial intelligence depends on the presence of an identifiable and preventable operational problem. When downtime is already within a normal range, the absence of cost reduction should not be considered a failure. Rather, it indicates that the model did not impose unnecessary intervention or artificially reduce reported costs.

At the Najaf Cement Plant, artificial intelligence produced the largest direct reductions, with annual unit-cost improvements ranging from 5.70% to 10.60% and downtime reductions ranging from 7.00% to 13.36%. The strongest effect occurred in 2023, when operational instability and unit costs were especially high. These results suggest that predictive maintenance and adaptive scheduling are most valuable in capital-intensive industries where equipment failure, production interruptions, and idle capacity impose substantial costs. The finding is consistent with delegated-monitoring theory, according to which specialized information processors create value by collecting information and intervening when monitoring benefits exceed monitoring costs [23]. Artificial intelligence performed a comparable function internally by continuously examining operational data and identifying conditions requiring managerial or maintenance intervention. Its predictive role also resembles reputation-based monitoring, in which accumulated information improves the reliability of future decisions [24].

At the Baghdad Soft Drinks Company, annual unit-cost reductions attributable to artificial intelligence ranged from 0.57% to 1.143%. Although modest, these improvements were stable across the five-year period. The principal contribution of artificial intelligence in this company was the stabilization of production schedules and reduction of operational variability rather than a large direct cost reduction. At the Iraqi Carpet Company, unit-cost reductions ranged from 0.14% to 5.66%. Because carpet manufacturing is labor-intensive, better scheduling and continuity improved the visibility of actual costs that might otherwise be obscured during interrupted or inefficient production periods. Thus, the accounting benefit involved more accurate measurement as well as cost reduction. This finding supports the broader proposition that information systems can improve managerial decisions even when their direct financial effect is limited. Research on bank-affiliated directors similarly indicates that access to specialized information can influence cash management, accounting policies, risk oversight, and reporting quality without necessarily producing identical outcomes in every organizational setting [30, 33-35].

The cross-company differences demonstrate that organizational and industrial characteristics condition the effects of technology. In capital-intensive cement production, MILP and artificial intelligence primarily improved resource allocation, maintenance, and unit-cost control. In the Baghdad beverage operation, the main benefits involved more accurate cost classification, schedule stability, and forecasting. In the labor-intensive carpet company, the largest benefits arose from correcting overhead assignments and reducing extreme cost variability. This contingency-based interpretation is compatible with evidence that monitoring arrangements differ according to institutional structures, financing relationships, and organizational characteristics [25-27]. It also corresponds with research showing that the effects of governance and bank involvement depend on the incentives and environments in which monitoring occurs [28, 31, 32]. Technology should therefore not be treated as a standardized intervention whose value is independent of production systems, cost structures, or data characteristics.

The results additionally have implications for profitability, governance, and risk management. More accurate cost information strengthens pricing decisions, production planning, budgeting, and capital allocation. It can also reduce the free-cash-flow problems associated with inefficient spending because managers obtain clearer evidence concerning idle resources, avoidable downtime, and unproductive activities [3, 4]. Improved cost visibility may reduce firm-specific uncertainty and support more rational investment decisions, particularly where managers face uncertainty regarding future production costs and resource availability [39]. From a capital-market perspective, the improvement of internal cost information may ultimately strengthen the quality of reported earnings and book values, thereby improving their usefulness for valuation and risk assessment [5, 38]. In addition, stronger information systems can complement legal and governance protections by increasing transparency and reducing opportunities for resource diversion or reporting manipulation [36].

The findings also complement recent evidence concerning digital transformation and financial performance in emerging Arab markets. Fintech adoption can improve profitability by increasing processing efficiency, reducing information costs, and supporting faster managerial responses [42]. The present results demonstrate that similar mechanisms operate in industrial manufacturing: digital technologies create value when they integrate accounting and operational information and convert it into actionable decisions. Moreover, the improved tracing of energy, materials, downtime, and waste may contribute to environmental and social performance by identifying inefficient resource consumption. This interpretation is relevant because environmental performance and corporate responsibility are associated with reporting incentives and accounting behavior [40, 41]. The technological system studied here may therefore support not only cost efficiency but also more transparent and responsible resource management.

Overall, the findings confirm that the integrated use of mixed-integer linear programming, big data analytics, and artificial intelligence strengthens cost-accounting systems through complementary mechanisms. MILP improves the logical allocation of resources and indirect costs; big data analytics increases cost stability and reduces measurement and forecasting errors; and artificial intelligence supports adaptive scheduling and predictive maintenance. These improvements are consistent with the general conclusion that monitoring and reporting quality depend on the availability, processing, and disciplined application of information [29, 43]. They also indicate that technology can supplement traditional governance, auditing, and control mechanisms by providing continuous, granular, and operationally grounded information. Accordingly, the study's hypotheses were broadly supported, although the magnitude and consistency of the effects depended on each company's production technology, cost structure, data stability, and level of operational disruption.

This study has several limitations that should be considered when interpreting the findings. First, the empirical analysis was restricted to four Iraqi industrial units, including two cement plants, one beverage company, and one carpet company; therefore, the results may not be directly generalizable to all Iraqi industries or to firms operating under substantially different economic and technological conditions. Second, the companies differed in their accounting systems, output units, production scales, and availability of operational data, which limited direct numerical comparisons across organizations. Third, some variables, particularly detailed downtime data for the Baghdad Soft Drinks Company, were unavailable, and proxy indicators were consequently used to evaluate operational stability. Fourth, the 2020–2024 period included the COVID-19 pandemic and episodes of economic and supply-chain instability that may have influenced production, costs, and demand despite the use of simulations and sensitivity analyses. Fifth, the reported improvements were derived from applied modeling and before-and-after comparisons rather than from a randomized experimental design, meaning that other contemporaneous operational or managerial changes may have contributed to some of the observed differences.

Future studies should examine a larger and more diverse sample of Iraqi industrial firms, including petrochemical, pharmaceutical, food-processing, construction-material, and machinery companies, to determine whether the findings remain stable across different cost structures and production technologies. Longitudinal research covering a longer postimplementation period would help assess whether the benefits of the integrated technological model persist after organizational learning and system adaptation. Researchers should also compare alternative optimization algorithms, machine-learning architectures, and anomaly-detection methods to identify which combinations are most effective under different levels of data complexity. Future work could employ quasi-experimental designs, matched control firms, interrupted time-series analysis, or difference-in-differences models to isolate the causal effects of technology adoption. Additional research should incorporate environmental costs, energy efficiency, carbon emissions, product quality, inventory turnover, employee productivity, and customer-demand uncertainty into the integrated model. The organizational factors affecting adoption, including employee digital competence, managerial support, cybersecurity readiness, data governance, and resistance to technological change, should also be investigated.

Iraqi industrial companies should implement modern accounting and operational technologies through a phased integration strategy rather than as isolated software applications. Firms should first standardize cost classifications, production codes, cost drivers, and data-collection procedures before deploying optimization and artificial-intelligence models. Internet of Things sensors and automated production records should be connected to accounting systems so that material use, energy consumption, machine status, output, defects, and downtime can be monitored in real time. Managers should establish multidisciplinary teams comprising management accountants, production engineers, data analysts, maintenance specialists, and information-technology personnel to validate model outputs and translate them into operational decisions. Technology should be configured according to the specific cost structure of each industry, with greater emphasis on predictive maintenance in equipment-intensive plants and on labor, process variability, and cost-tracing accuracy in labor-intensive industries. Regular model validation, cybersecurity controls, staff training, and managerial review should be institutionalized to ensure that technological outputs remain accurate, explainable, and practically useful.

Authors' Contributions

Authors equally contributed to this article.

Ethical Considerations

All procedures performed in this study were under the ethical standards.

Acknowledgments

Authors thank all participants who participate in this study.

Conflict of Interest

The authors report no conflict of interest.

Funding/Financial Support

According to the authors, this article has no financial support.

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