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Enhancing the Production Efficiency of Construction Materials Enterprises through Systemic Management of Technological and Economic Processes

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Abstract

The study analyzes the distinctive features of improving the production efficiency of enterprises in the construction materials industry in the context of accelerating technological restructuring and the institutionalization of the "Industry 4.0" paradigm. The relevance of the topic is determined by the need to eliminate managerial discontinuity manifested as misalignment between the high-frequency dynamics of technological loops and the comparatively inert economic mechanisms of planning and control, which creates a persistent gap between actual production regimes and managerial decision models. An algorithm of systemically integrated production management, ASIM-CMP (Algorithmic Systemic Integration Model for Construction Materials Production), is proposed; it is grounded in organizational cybernetics and in Stafford Beer's Viable System Model (VSM). This construct is interpreted as an instrument for aligning goals, information flows, and feedback loops, ensuring coherence across managerial levels and the stability of the production system under disturbances originating in both external and internal environments.

The research provides an extended characterization of the global construction materials market with segmentation across the key categories—cement, concrete, and metal structures—and identifies the drivers underpinning the most pronounced growth trajectory in the Asia–Pacific region and North America. On this basis, the expediency of shifting from isolated control loops to integrated architectures is substantiated, wherein coupling between ERP and MES layers is implemented as a unified information space supported by the industrial Internet of Things (IoT) and digital twin technology as means of continuous synchronization of data, equipment states, and production scenarios.

A substantial part of the study is devoted to the formalization of efficiency-enhancement tasks: mathematical formulations for optimizing resource consumption are presented, along with tools for techno-economic verification of implementing decarbonization solutions, including Power-to-Methane and carbon capture and storage (CCS) technologies. The results indicate the feasibility of multiple-factor productivity strengthening—up to 2.4×—with a concurrent reduction in operating costs of 15–20% when a systemic approach is applied based on integrating technological and managerial loops. The material is organized in accordance with the IMRAD logic and is oriented toward the professional community engaged in industrial management and digital transformation.

Keywords: Construction materials industry, systemic managemen, Industry 4.0, production efficiency, ERP–MES integration, viable system model, digital twin artificial intelligence, decarbonization, cybernetic approach

Introduction

The global construction materials industry in the period under consideration exhibits signs of deep structural reconfiguration driven by the combined impact of large-scale macroeconomic shifts and the acceleration of technological innovation. Market reviews for 2024–2025 estimate the global industry volume at USD 1.56 trillion, with expected expansion to USD 2.26 trillion by 2033 at an average annual growth rate of approximately 4.2% (CAGR) [1]. This trajectory is supported by persistent demographic and urbanization trends, as well as rising intensity of commercial and infrastructure projects; at the same time, the highest concentration of demand and investment activity is observed in the Asia–Pacific region, which accumulates about 49% of the aggregate market [1].

Despite outwardly favorable quantitative indicators, the sector faces a set of systemic constraints. A key factor is pronounced volatility in prices for energy resources and raw material components, which, together with rising logistics costs, exerts pressure on margin performance and increases uncertainty in production and sales planning. The average level of global construction-cost inflation in 2024 is estimated at 4.15%; however, regional variability can reach extreme values due to currency instability and disruptions in supply chains [4].

An additional contour of challenges is associated with the regulatory and economic pivot toward a “green” growth model. Construction materials production belongs among the most carbon-intensive segments and is associated with more than 7% of anthropogenic greenhouse gas emissions, which objectively increases regulatory and investment pressure on enterprises [5]. Under these conditions, competitiveness is increasingly determined by the capacity to deploy capital-intensive decarbonization technologies and to transition to alternative fuel and raw-material trajectories—paths that require not only equipment modernization but also reconfiguration of management loops for quality, energy, and costs.

Against the backdrop of a more complex external environment, traditional production management models built on rigid hierarchy and the functional separation of subsystems through which equilibrium is achieved between operational autonomy of units and engineering and financial-economic units lose sufficiency in terms of adaptiveness. When the complexity of the controlled object exceeds the regulatory capacity of internal mechanisms, a crisis of controllability emerges, expressed in slower responses to disturbances, increasing losses at functional interfaces, and reduced accuracy of planning and accounting models. As a methodological response, the study considers a systemic paradigm in which an enterprise is treated not as the sum of departments, but as an integral cybernetic construct endowed with mechanisms of self-organization and adaptive behavior [7].

The purpose of the study is the development and scholarly verification of a methodology for enhancing production efficiency through the systemic integration of digital technologies, the apparatus of mathematical modeling, and a set of organizational transformations.

The author’s hypothesis is based on the assumption that sustained growth in production efficiency of construction materials enterprises is achieved when technological loops (OT) and economic planning/control mechanisms (IT) are consolidated into a single closed control loop with continuous feedback, eliminating time lags and the “discreteness” of managerial interventions.

The scientific novelty of the work consists in developing and substantiating the algorithmic model of systemically integrated management ASIM-CMP, which—first, for construction materials enterprises—formally couples the VSM levels of S. Beer with the Industry 4.0 technology stack (IoT–MES–digital twins/AI–ERP) and embeds techno-economic optimization (including CO_2 constraints) into a unified cybernetic decision-making mechanism.

Materials and Methods

The methodological foundation of the study is formed through an interdisciplinary integration of systems analysis, industrial cybernetics, and contemporary doctrines of production management. As the basic theoretical instrument, Stafford Beer’s Viable System Model (VSM) is adopted; it provides a strict decomposition of an organization into five functional

centralized loops of coordination and control [7]. The applicability of this approach to the construction materials industry is determined by the spatial distribution of the production-logistics architecture, which includes quarries, clinker-stage facilities, grinding capacities, and logistics hubs.

Assessment of the effectiveness of digital transformation relied on bodies of systematic literature reviews aggregating recent publications, as well as on empirical materials extracted from Scopus and Web of Science datasets. Priority attention was focused on studies disclosing the substance and toolkit of the Construction 4.0 concept, which transfers the principles of the fourth industrial revolution—IoT, AI, Big Data, and robotics—into the construction sphere and its adjacent industries [8, 9].

The mathematical toolkit is represented by multi-criteria optimization methods oriented toward solving mix-design tasks and rational resource allocation. The use of linear and dynamic programming models enabled the formulation of cost-minimization problems while simultaneously meeting strictly regulated requirements for strength and environmental safety of materials [12]. Verification of modernization trajectories for cement production was carried out on the basis of techno-economic analysis (TEA), allowing comparison of upgrade scenarios integrating carbon capture and storage (CCS) and hydrogen-energy solutions [5].

The empirical corpus included analytical reports by leading international agencies (SkyQuest, Fortune Business Insights, Precedence Research, Deloitte), as well as practice-oriented cases of implementing digital solutions at leading enterprises in Europe, North America, and Asia [1]. Data formation and processing were implemented using bibliometric mapping and qualitative content analysis methods, which enabled identification of stable correlational relationships between the level of enterprises' digital maturity and their financial outcomes [17].

Results and Discussion

The development of the global construction materials industry in 2024–2025 is characterized by a distinctly expressed cyclicality, in which the leading impulse is formed by infrastructure construction. The aggregate market volume in 2025 is estimated at USD 1.42 trillion, with a forecast of exceeding USD 2.09 trillion by 2035 [3]. The largest segment by share remains construction aggregates (sand, crushed stone), accumulating over 42% of market volume; at the same time, accelerated dynamics are observed in niches of structural metals and innovative composites, where expansion rates noticeably outpace the market average [1].

Under the prevailing conjuncture, the economic performance of production is determined not so much by scale effects as by the ability to manage costs operationally on the basis of data arriving in a near real-time regime. Available statistical estimates indicate that the average profit margin in commercial construction on large projects is about 8.4%, whereas on small-scale projects it reaches 10.6% [4]. This gap reflects the heightened managerial complexity of large-scale production–construction systems, where growth in project size is accompanied by non-linear complication of coordination, strengthening of transactional losses, and increased sensitivity to price and logistics disturbances—thereby creating demand for instruments that measure and controllably constrain complexity.

Key macroeconomic indicators of sector development, which define the context for implementing efficiency-enhancement strategies, are aggregated in Table 1.

Table 1. Global indicators and forecasts of the construction materials market (compiled by the author based on [1, 2, 4, 9, 18]).

Indicator	Value (2024–2025)	Forecast (2033–2035)	CAGR (%)
Total market volume (USD bn)	1,560	2,260	4.2

Asia–Pacific share (%)	48.8	51.2	4.9
"Construction 4.0" technologies market (USD bn)	16.0	48.0	14.9
Digital twins market in construction (USD bn)	1.49	18.87	32.6
Construction cost inflation (average, %)	4.15	3.90	—

Analysis of the indicators in Table 1 records a pronounced imbalance between the dynamics of the traditional market (4.2%) and the growth rates of the digital segment in the industry, reaching 14.9%–32.6%. This contrast signals a shift of competition into the plane of digital maturity: data and algorithmics become determining factors of resilience, whereas refusal to implement data-driven systemic management predictably increases the probability of losing positions due to uncontrolled cost expansion and insufficient adaptiveness to price, logistics, and regulatory disturbances.

Within the study, an authorial concept is formed—an algorithmic model of systemic integration of construction materials production (ASIM-CMP)—based on coupling the five VSM levels with the Industry 4.0 technology stack. The principal problem of traditional managerial architectures consists in the misalignment of OT (Operational Technology) and IT (Information Technology) loops, functioning in different temporal and logical regimes, which provokes delays in managerial interventions and information gaps between production reality and economic models. ASIM-CMP removes this contradiction through the formation of a single cybernetic loop in which technological parameters and financial-economic metrics are connected by continuous data streams and feedback mechanisms [26, 27].

The ASIM-CMP architecture is interpreted as a multi-level system in which the sensor layer (IoT) ensures the collection of streaming data in real time from temperature, pressure, vibration, and energy-consumption sensors on technological lines, including critical units such as rotary kilns in cement production [8]. The execution layer (MES) implements dispatching of production orders, quality control, and batch traceability, and also synchronizes the actual process durations with planned parameters, ensuring comparability of technological and managerial time scales [20]. The analytical layer, combining digital twins and artificial intelligence tools, forms a computational environment for wear forecasting and adaptive optimization of operating regimes aimed at minimizing scrap and energy intensity; predictive AI agents are considered a means of reducing the risk of sudden shutdowns by approximately 20% [15]. The resource planning layer (ERP) covers financial accounting and procurement and sales functions; integration with MES shifts the calculation of unit cost from a retrospective reporting-period format to a near real-time regime, which fundamentally increases the controllability of margins [21]. The upper contour of strategic adaptation, corresponding to VSM (System 4/5), provides assessment of market risks, consideration of constraints under environmental quotas (CO_2), and formation of long-term investment decisions on the basis of reliable data arriving from the lower levels [7].

A key constructive element of the model is a closed feedback loop between the economic outcome and the technological parameter, ensuring automated alignment of production regimes with changing market conditions. As an illustrative mechanism, the situation of a sharp increase in electricity prices on the spot market is considered, under which ASIM-CMP recalculates the optimal cement grinding regimes, finding a new compromise between productivity and energy costs without loss of controllability.

Coupling ERP and MES is treated as a source of techno-economic synergy, because it is precisely the gap between the administrative-financial contour and the production site that forms one of the most critical problems for construction materials enterprises. In the absence of integration, data on execution of the production program, actual raw-material consumption, and quality deviations arrive with substantial delays, making operational management of margin and unit cost methodologically and technologically difficult [20, 25].

Systemic integration forms a "single source of truth" for the organization, reducing the probability of discrepancies in accounting interpretations and ensuring the consistency of managerial decisions at all levels.

Empirical estimates confirm the quantitative significance of the effect: studies from 2024 show that automation of data transfer between the production contour and the financial block can deliver savings of up to USD 1 million per year at a single large enterprise by eliminating manual entry errors and the associated losses in data quality [20]. A comparison of performance indicators before and after the implementation of an integrated management system is presented in Table 2.

Table 2. Impact of systemic ERP–MES integration on production KPIs (compiled by the author based on [17, 19, 20]).

Performance indicator	Before integration (traditional approach)	After integration (systemic approach)	Improvement (%)
Time for production planning (days)	3–5	<1	80+
Unit-cost forecasting accuracy (%)	75–80	98	20+
Reduction in inventory carrying costs (%)	—	15	15
Unplanned equipment downtime (%)	12	6	50
Reduction in data-processing labor (hours/week)	40+	10	75

For the implementation of systemic management, mathematical models are required that link the physical properties of materials with their cost characteristics. In the production of concrete and reinforced concrete products, the principal task is the search for an optimal dosage of components (cement, aggregates, admixtures).

The author's mathematical model for optimizing cost C under a given vector of technical requirements T (strength, frost resistance, environmental performance) has the following form:

$$min\ C(x) = \sum_{i=1}^{n} (p_i + l_i + \tau_i e_i)\, x_i \quad (1),$$

Where:

p_i is the purchase price of a unit of the ith component;

l_i is the logistics costs per unit of the ith component;

τ_i is the carbon tax/penalty rate for the ith component (sometimes a single τ);

e_i is the specific CO2 emission per unit of the component;

$\tau_i e_i$ is the monetary equivalent of the carbon footprint in terms of cost.

Experimental results indicate that the introduction of machine-learning algorithms for the operational correction of the water-to-cement ratio—accounting for the actual aggregate moisture content in a

near real-time regime—ensures a 10–20% reduction in specific cement consumption while preserving the required design strength of the material [12]. Given the current cost of cement, this effect translates into a direct reduction of total product unit cost at the level of 5–8%, reflecting the high sensitivity of economic outcomes to the accuracy of managing mix-design parameters and to the quality of streaming data in the technological contour **(see Fig. 1).**

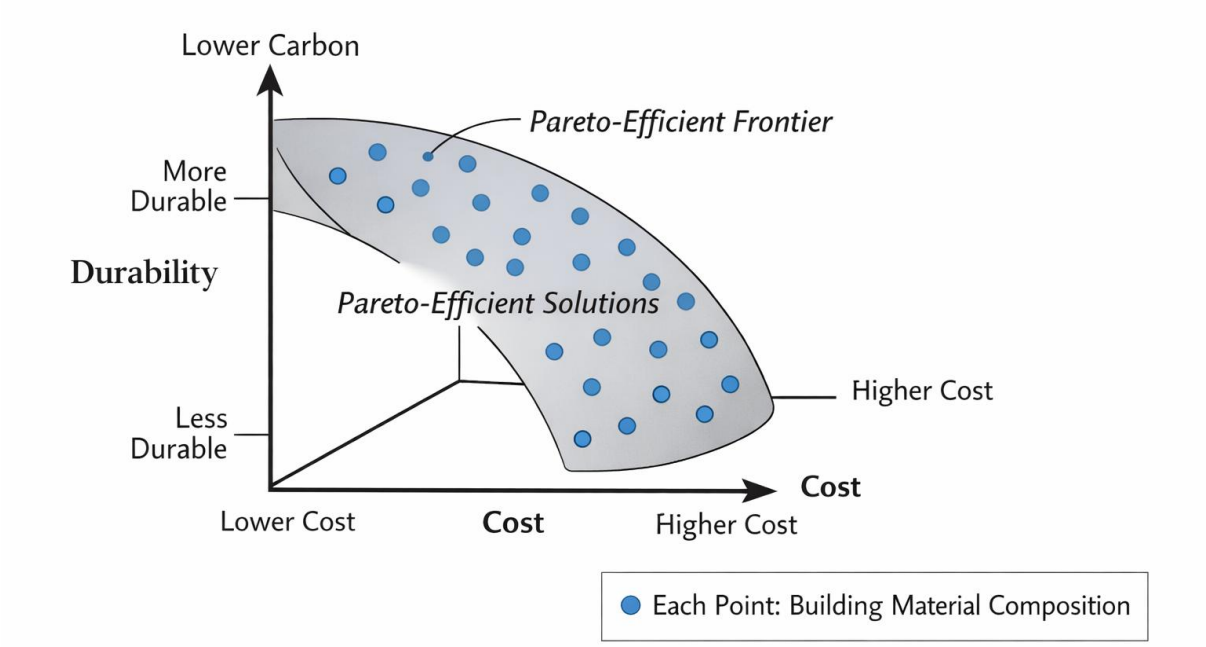

Fig.1. Multi-Criteria Optimization (compiled by the author based on [12, 22, 23]).

Implementation of systemic management shifts the boundary of economically attainable operating regimes toward the area of lower costs, ensuring an additional cost reduction of 12–15% [12]. Such an effect is interpreted as the result of synchronizing technological parameters and economic criteria within a single decision-making loop, where optimization ceases to be a local function of individual sections and acquires the character of an end-to-end configuration of the entire production system.

The critical dependence of construction materials enterprises on the reliability of heavy equipment—rotary kilns, crushing units, and conveyor lines—predetermines the central role of asset life-cycle management in the structure of operational efficiency. Within a systemic approach, a transition from traditional scheduled preventive maintenance to condition-based maintenance is expedient, grounded in continuous monitoring of parameters and predictive signal processing [8]. In this logic, a digital twin of a cement kiln, applying deep-learning methods, performs analysis of spectral combustion characteristics and vibration features associated, among other aspects, with the condition of bearing assemblies, enabling early identification of anomalies hundreds of hours before a potential failure [11, 13].

The effects of implementing such solutions in capital-intensive industries are expressed not only in reducing the risk of emergency shutdowns, but also in measurable economic results: according to McKinsey estimates, the use of predictive systems can reduce maintenance costs by approximately 18% and increase equipment utilization by 10–15%, which directly transforms into output growth under a fixed asset base and into a reduction of losses associated with unplanned downtime [17].

Further, Table 3 presents the economic indicators of implementing AI technologies and predictive analytics.

Table 3. Economic indicators of implementing AI technologies and predictive analytics (compiled by the author based on [6, 17, 28]).

Technological module	Maintenance savings (%)	Revenue growth (x)	Average ROI	Examples of effects
Predictive diagnostics	18–25	2.5	3.7×	Downtime reduction by 20%
Energy consumption optimization	10–15	1.8	4.2×	Fuel cost reduction
Autonomous logistics (drones)	30	1.5	5.1×	Reduced inspection costs
Digital quality control	15	2.1	10.3×	Scrap reduction by 30%

Economic performance within the contemporary development contour is increasingly determined by environmental constraints and the cost of the carbon footprint; a managerial system that does not incorporate costs associated with CO_2 emissions loses viability under tightening regulation and changing investment criteria. In the cement industry, this manifests as intensified research and deployment of decarbonization solutions, primarily through integrating technologies for capturing and treating exhaust gases [5].

Among the most promising directions is the P2M-CC concept (Power-to-Methane with carbon capture), within which surplus renewable-energy generation is converted into hydrogen, and the latter is then used in a reaction with CO_2 captured from kiln gas to produce synthetic methane [14]. Returning the synthesized methane to the kiln as fuel forms a closed carbon–energy cycle in which technological solutions for CO_2 utilization simultaneously function as an instrument for managing the fuel balance.

Results of techno-economic elaboration demonstrate substantial effects: the CO_2 emissions factor may decline from 789 to 85 kg per ton of cement, corresponding to a reduction of approximately 89% [14]. At the same time, it is noted that integrating waste-heat recovery (WHR) systems in modern kilns makes it possible to raise energy efficiency to a level of about 90%. Capital expenditures for such complexes remain materially higher than standard solutions—approximately 2–3×—yet under scenarios of high carbon taxes, operating costs can decrease by 58% relative to the baseline trajectory. In this logic, systemic management transfers environmental investments from the category of "non-productive burden" into the domain of tools for optimizing long-term financial flows, while simultaneously increasing access to "green" financing and resilience to regulatory risks.

Despite pronounced advantages, the transition to systemic management based on Industry 4.0 is constrained by a set of barriers. The most significant limitation is a shortage of personnel possessing competencies at the intersection of IT and industrial production; according to Deloitte, more than 35% of executives qualify workforce adaptation to "factories of the future" as the primary challenge of transformation [16]. An additional obstacle is technological fragmentation: a typical enterprise operates up to 10 heterogeneous applications that form isolated "information wells" [24]. A substantial share of decision-makers (about 75%) indicate excessive time expenditures

associated with coordinating disparate data arrays, emphasizing the necessity of transitioning to open architectures and solutions with high interoperability [29, 30].

A rational transformation strategy under such conditions can be represented as a sequence of interconnected steps. The initial contour includes building a digital foundation through the implementation of cloud platforms and data standardization as prerequisites for comparability and scalability of solutions [16]. Next, implementation of pilot initiatives focused on predictive maintenance for selected critical units is advisable, allowing measurable effects to be obtained and the deployment methodology to be tested within a limited perimeter [31, 32]. The final contour is associated with scaling and institutionalizing changes: retraining personnel and embedding new management practices through combining Lean Construction principles with digital instruments that ensure data discipline and the reproducibility of improvements [10].

Conclusion

The results confirm the stated hypothesis that systemic linkage of technological and economic management loops constitutes a foundational condition for the resilience and competitiveness of construction materials enterprises in the era of digital transformation. The shift from fragmented control to an integral cybernetic organization of management ensures not only local optimization of current costs, but also forms an institutionally and technologically embedded platform for long-term sustainable development, including adaptation to market volatility and environmental constraints.

A key scientific and applied result is the formation of the ASIM-CMP model as an innovative management architecture in which the principles of Stafford Beer's VSM are coupled with the Industry 4.0 technology stack, ensuring "seamless" continuity between measurements of the production contour and the financial-economic reporting of the administrative level. The evidence base for quantitative efficiency rests on the conclusion that full-scale integration of ERP and MES increases planning accuracy to 95% and reduces production losses by 15–20%, reflecting the elimination of time lags, errors in data interpretation, and misalignment of managerial decisions. A substantial contribution is the substantiation of the role of predictive analytics, digital twins, and AI tooling: these solutions are shown to be capable of delivering returns on investment at the level of 3.7×–10.3× with a twofold reduction in equipment downtime, demonstrating their status not as auxiliary, but as system-forming elements of contemporary production efficiency.

A separate contour of results concerns coupling economic and environmental criteria. It is shown that a systemic approach to decarbonization based on the P2M-CC technological linkage enables radical reduction of CO_2 emissions—up to 89%—while preserving the long-term economic feasibility of production, transferring environmental investments into the category of manageable financial decisions rather than forced costs. In this way, a methodological basis is formed for considering environmental sustainability as an integral factor of efficiency influencing cost structure, access to financing, and regulatory risks.

The practical implication of the results consists in the necessity to treat digital transformation not as a one-time implementation of a software product, but as a comprehensive organizational reconfiguration requiring investment in human capital and the institutionalization of a data-driven management culture. Prospects for further research logically shift toward analyzing network effects arising from inter-firm integration of management systems within unified value chains, including the formation of "smart" supply chains and distributed decision-making loops at the level of industry ecosystems.

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