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Optimisation of Medical Examination Management Systems Through Digitalisation: An Architectural Approach and Economic Evaluation

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Abstract: This article develops and theoretically substantiates a didactic management model for employee medical examination processes based on digitalisation, incorporating a three-layer IT architecture (presentation, business logic, and data layers) and an integrated mechanism for economic efficiency evaluation. The relevance of the study is determined by the systemic shortcomings of the traditional paper-based medical records model: excessive time and administrative costs, high probability of documentation errors, and the absence of analytical tools for the timely detection of deviations in employees' health status. The proposed architectural model of the medical examination management system (MEMS) is implemented as a microservices application with cloud data storage and API integration with HR and governmental medical information systems. The model was validated in eight organisations of the Republic of Uzbekistan with a total workforce of 3,740 employees. The experimental results confirmed the high operational and economic effectiveness of the proposed solution: the average processing time per medical examination decreased by 71.2% ($p < 0.001$), administrative costs fell by 65.8% ($p < 0.01$), and the return on investment index (ROI) reached 218% during the second year following implementation. The findings offer practical value for organisational managers, digital transformation specialists, and policymakers in the field of occupational health.

Keywords: digitalisation, medical examination management, IT architecture, economic efficiency, microservices architecture, digital transformation, information system, occupational health, ROI, business process optimisation, electronic medical records, Uzbekistan.

Introduction

The digital transformation of management processes ceased long ago to be the exclusive domain of high-technology industries. Today it penetrates areas historically characterised by conservatism and resistance to innovation — including occupational health and the organisation of medical examinations. This is no coincidence: it is precisely here that some of the most acute operational and economic challenges of modern human resource management are concentrated. Multi-stage paper documentation, fragmented medical archives, inefficient examination scheduling, and delayed identification of occupational risks all entail direct economic losses, legal exposure and, crucially, genuine threats to personnel health.

In the context of contemporary Uzbekistan, this problem takes on particular urgency. The intensive development of the industrial and agro-industrial sectors, the expanding services economy, and growth in the employed population place before the state and employers the task of building effective personnel health monitoring systems. Yet research demonstrates that in the majority of domestic organisations, employee medical records continue to be maintained in the traditional paper format, making the process labour-intensive, costly and of limited informational value from a management perspective.

The present study aims to develop and substantiate a model for the digital management of employee medical examination processes — one that is architecturally rigorous, economically measurable and practically replicable. Unlike existing partial solutions, the proposed model treats the medical examination process as a systemic whole: from scheduling and conducting examinations through to the generation of analytical reports and integration with HR and governmental medical information systems.

The relevance of the study is further supported by the national digital transformation agenda. In accordance with the Digital Uzbekistan — 2030 Strategy and the decrees of President Sh. M. Mirziyoyev on the development of the digital economy, the digitalisation of management processes in the social sphere — including healthcare and occupational safety — has been designated a strategic national development priority. The present research directly aligns with the implementation of this agenda.

Literature Review and Theoretical Foundations

The digitalisation of employee health management processes is studied from several theoretical perspectives, whose intersection constitutes the methodological foundation of this work.

The key conceptual basis is the theory of digital transformation of business processes. G. Westerman, D. Bonnet and A. McAfee, in their landmark study *Leading Digital*, persuasively demonstrate that successful digital transformation is realised not as the mere automation of existing processes, but as their fundamental reconceptualisation grounded in digital capabilities [3]. Applied to medical document management, this means that it is insufficient to 'digitise' paper records — the entire examination management process must be restructured, including scheduling logic, data verification and analytics.

In the domain of information systems architecture for healthcare, the work of R. Lenz and M. Reichert is of foundational significance; they investigated the specifics of business process modelling in medical information systems [1]. The authors substantiate the advantages of process-oriented architectures over traditional monolithic systems: the former provide flexibility in adapting to changing regulatory requirements and substantially reduce maintenance costs. This conclusion was further developed in the concept of microservices architecture, systematically set out by S. Newman and recognised as the most promising approach for building scalable enterprise information systems.

The economic evaluation of digital transformation projects constitutes an independent theoretical challenge. Classical investment appraisal methods (NPV, IRR, ROI) are applicable to IT projects only with significant qualifications: a substantial portion of the benefits from digitalisation is intangible or difficult to quantify. T. Kohli and V. Grover, analysing the business value of IT investments, proposed an extended evaluation model that accounts not only for direct financial effects but also for operational improvements, enhanced decision-making quality and reduced regulatory risk. In the present study, this model has been adapted to the specifics of medical examination management [2].

The digitalisation of occupational safety and employee health monitoring has been actively studied in the international scientific literature in recent years. P. Schulte and G. Bhatt substantiate the necessity of transitioning to predictive occupational risk

management models, the implementation of which is possible only on the basis of centralised digital databases on employee health status. Similar conclusions are contained in the work of M. Harber and R. Redlich, who studied the effectiveness of electronic medical record systems compared to paper-based ones: the authors recorded a 31–47% reduction in the frequency of missed diagnoses in organisations that had implemented digital personnel health monitoring systems.

In the domestic scientific literature, the digitalisation of personnel management and occupational safety systems has been studied considerably less intensively. Among relevant Uzbek contributions, the work of T. A. Rashidov [9], who systematised approaches to the digital transformation of public administration, and M. B. Ismailov [3], who examined the economic aspects of information system implementation in the social sector of Uzbekistan, merit particular mention [4].

Methodology

Nevertheless, the specific features of medical examination management as an independent object of digitalisation have received virtually no attention in the domestic literature, which confirms the scientific novelty of the present study.

A critical analysis of existing solutions reveals three key deficiencies. First, the majority of available medical record information systems have been developed for clinical institutions and are poorly adapted to the corporate context. Second, the economic efficiency of digitalising medical examinations is generally measured on the basis of a limited set of indicators (typically time costs alone), without accounting for the full spectrum of financial and operational benefits. Third, the integration capabilities of existing systems with HR and governmental medical information systems remain insufficiently developed. The development of a model free from these limitations constitutes the scientific novelty of the present study.

Result and Discussion

Architectural Model of the Medical Examination Management System

The proposed Medical Examination Management System (MEMS) is built on the principles of microservices architecture and is organised into five interrelated layers. A detailed description of the components of each layer is provided in Table 1.

Table 1. Architectural Model of the Medical Examination Management System (MEMS).

Architecture Layer	Component	Functions and Characteristics
Presentation Layer	Web portal, mobile application (PWA)	Appointment registration, results entry, report generation. Responsive interface with iOS/Android/Web support.
Business Logic Layer	Microservices application core	Modules: 'Examination Scheduling', 'Electronic Journal', 'Analytics & Monitoring', 'Integration Gateway'. Communication via REST API / gRPC.
Data Layer	Relational DB + document store	PostgreSQL — structured data; MinIO — medical documents and scanned copies. Daily backup using 3-2-1 strategy.
Security Layer	Identity and protection subsystem	OAuth 2.0 / OpenID Connect, role-based access control (RBAC), data-at-rest encryption (AES-256) and in-transit encryption (TLS 1.3), action audit log.

Architecture Layer	Component	Functions and Characteristics
Integration Layer	API gateway, adapters to external systems	Bidirectional integration with the HR system (1C: Enterprise), national medical registries and the electronic document management system.

The key architectural decision is the separation of the system into independent microservices, each implementing a strictly bounded functional domain. This provides three critically important operational properties.

First, independent scalability: during scheduled medical examination periods (typically annual), the load on the 'Examination Scheduling' module increases 8–12 fold while the other modules operate normally — the microservices architecture allows only the overloaded component to be scaled without expanding the capacity of the entire system [5], [6].

Second, isolated updates: changes in regulatory requirements regarding medical document formats (which occur regularly in domestic practice) entail updating only the relevant microservice, leaving the rest of the system unaffected.

Third, independent fault tolerance: a failure in the analytics module does not interrupt the registration of examination results [7].

The 'Examination Scheduling' module implements automatic schedule generation based on regulatory requirements for the frequency of examinations across different personnel categories. The scheduling algorithm accounts for occupational hazard classification, employee age, previous examination results and the availability of medical specialists. Automated notifications are sent to the employee and their supervisor 30, 14 and 3 days before the scheduled examination, effectively eliminating missed appointments.

The 'Electronic Journal' module provides digital registration of examination results in a structured format. The physician enters data directly into the system through a secured interface; the system automatically checks the completeness of the entered data and detects anomalies (values outside reference ranges) in real time [8]. This represents a fundamental departure from the traditional model, under which abnormal indicators are frequently discovered only during retrospective analysis of medical records — or not discovered at all.

The 'Analytics and Monitoring' module generates dynamic dashboards for different user categories: organisational management (aggregated workforce health indicators), occupational safety specialists (trends in occupational risks by department) and medical personnel (individual trends for each employee) [9]. The system supports report exports in formats compliant with the requirements of regulatory authorities.

A crucial architectural element is the integration layer, which provides bidirectional communication with the organisation's HR system (synchronisation of employee, position and work schedule data), the national medical registries of the Ministry of Health of the Republic of Uzbekistan, and the organisation's electronic document management system. Integration is implemented via a standardised REST API with HL7 FHIR support for medical data, ensuring compatibility with future national medical information systems [10].

Table 2 presents a comparison of the key characteristics of the traditional medical examination system and the proposed digital model.

Table 2. Comparative Characteristics of the Traditional and Digital Medical Examination Management Systems.

Criterion	Traditional System	Digital System (proposed model)
Average processing time per examination	45–60 min	12–18 min (–68%)
Error rate in document completion	7.3%	0.9% (–87.7%)
Documentation storage costs (per 1,000 employees/year)	4,200,000 UZS	420,000 UZS (–90%)
Data availability for authorised personnel	Limited (physical storage)	24/7 (cloud access)
Analytical capabilities (health dynamics)	Minimal (manual aggregation)	Full-featured (BI dashboard)
Integration with HR system	None	Implemented via REST API
Compliance with personal data protection requirements	Partial	Full (AES-256 encryption)

Economic Evaluation Methodology

The economic evaluation of the proposed system was conducted using the total cost of ownership (TCO) methodology combined with an extended return on investment model. The structure of economic effects encompasses three groups.

The first group comprises direct, immediately measurable costs and savings: (a) reduction in personnel time costs for processing, retrieving and transferring medical documents; (b) reduction in expenditure on paper documentation, its storage and disposal; (c) reduction in costs associated with correcting documentation errors and reissuing medical conclusions.

The second group encompasses indirect effects measured through operational indicators: (a) a reduction in overdue scheduled examinations and associated administrative penalties; (b) a reduction in employee working time lost to waiting for certificates and medical conclusions; (c) a reduction in temporary disability sickness rates due to the timely detection of health deviations.

The third group comprises strategic effects amenable only to expert assessment: a reduction in regulatory risk (the risk of sanctions from supervisory authorities), an enhancement of the organisation's attractiveness as an employer, and the provision of an analytical foundation for long-term occupational safety planning.

ROI was calculated using the standard formula: $ROI = (NPV / \text{Total Implementation Costs}) \times 100\%$, where net present value (NPV) was calculated at a discount rate of 15% – consistent with the average cost of capital for organisations in the Republic of Uzbekistan. Total implementation costs include: software development and customisation, technical infrastructure (servers, network equipment), staff training and annual technical support costs.

Validation Results

The experimental validation was conducted in eight organisations of the Republic of Uzbekistan across various sectors (industry, construction, services) with a total workforce of 3,740 employees. System implementation was carried out in stages over eight months;

the comparative analysis was based on data from the baseline year (pre-implementation) and the second year post-implementation [11].

The results of the comparative analysis are presented in Table 3. A paired Student's t-test (for continuous indicators) and Pearson's χ^2 test (for proportional indicators) were applied to assess the statistical significance of differences. Statistically significant differences are indicated as follows: ** – $p < 0.01$; *** – $p < 0.001$.

Table 3. Dynamics of Medical Examination Management Efficiency Indicators Before and After Digital System Implementation (n = 8 organisations, 3,740 employees).

Indicator	Before Implementation (Baseline)	After Implementation (Year 2)	Change
Average processing time per examination (min)	52.4	15.1	-71.2%***
Share of documented violations detected on time (%)	41.3	78.6	+37.3 p.p.***
Number of overdue scheduled examinations (per 1,000 employees)	83	12	-85.5%***
Examination administration costs (million UZS/year per 1,000 employees)	18.7	6.4	-65.8%**
Average employee waiting time for a certificate (hours)	26.3	2.1	-92.0%***
Employee satisfaction with the examination procedure (score, 1–5)	2.7	4.3	+1.6 points***
Return on Investment Index (ROI, %)	—	218	+218%

Analysis of the data reveals several key patterns. First, the most pronounced effects were recorded for time-related indicators: the 71.2% reduction in examination processing time and the 92.0% reduction in employee waiting time for certificates together yielded total working time savings equivalent to an average of 14.3 million UZS per year per 1,000 employees at the standard hourly labour cost across the organisations studied.

Second, the quality of medical monitoring improved substantially: the share of timely detected documented violations rose from 41.3% to 78.6% (+37.3 p.p., $p < 0.001$) [12]. This is attributable primarily to the system's automatic generation of alert notifications when indicators fall outside established norms — in contrast to the traditional model, under which the physician must independently compare current data against previous examination results, which is practically unachievable at a workload of 20–30 examinations per day.

Third, the reduction in overdue scheduled examinations from 83 to 12 per 1,000 employees (-85.5%, $p < 0.001$) is of critical regulatory significance: it is precisely the non-completion of scheduled examinations that constitutes the most common basis for administrative sanctions in the field of occupational safety. In monetary terms, the reduction in regulatory risk is estimated at an average of 6.8 million UZS per year per 1,000 employees [13].

An ROI of 218% in the second year attests to the high investment attractiveness of the project. The average payback period was 14.2 months, which falls within the typical planning horizon for corporate IT projects in the Republic of Uzbekistan. It should be noted that this calculation includes only quantifiable effects; accounting for strategic benefits (regulatory risk reduction, improvement in decision-making quality), the real ROI is estimated by the authors at 280–320%.

Among the observations that merit special attention: the rate of positive effect achievement varied substantially depending on organisational digital maturity [14]. In organisations already possessing a developed IT infrastructure and HR information system, the full operational effect was achieved 3–4 months after launch. In organisations with low digital maturity, an equivalent result required 7–9 months and significantly greater investment in staff training. This finding has important practical implications: an assessment of organisational readiness for digital transformation should precede any decision to implement the system.

Discussion

The results obtained raise a number of theoretical and practical questions requiring specific examination [15], [16].

The first concerns the optimal deployment model. During the validation, three models were tested: cloud-based (SaaS), hybrid (data on +own servers, interface in the cloud) and on-premises (entirely on the organisation's own servers). Analysis demonstrated that the cloud model offers the lowest total cost of ownership and the fastest deployment, but meets with the greatest resistance from organisations handling personal medical data of high confidentiality [17]. The hybrid model represents the optimal compromise for the majority of domestic organisations: it permits personal data to be stored locally (in compliance with the requirements of the Republic of Uzbekistan's personal data protection legislation) while retaining the advantages of the cloud interface and analytical tools.

The second question concerns change management during system implementation [18]. The validation experience showed that technical barriers to implementation are substantially less challenging than organisational ones. The most significant resistance originated from medical personnel, who were concerned that the digital system would constrain their professional autonomy and create conditions for excessive monitoring of their activities. Overcoming this resistance required deliberate efforts to engage medical staff in the system design process at early stages, as well as targeted communication activities demonstrating that the system is a tool for supporting the physician's professional work rather than a surveillance instrument [19].

The third question relates to the scalability of the proposed approach. The validation results were obtained primarily from mid-sized organisations (300–600 employees). The applicability of the model to small enterprises (fewer than 50 employees) and large corporations (more than 5,000 employees) requires separate investigation: in both cases, the cost–benefit ratio changes substantially. For small enterprises, a promising solution is the development of a simplified SaaS version of the system with a minimal feature set, enabling basic digitisation of medical records at minimal investment [20].

The study's limitations are determined primarily by the sectoral heterogeneity of the sample: the eight participating organisations belong to substantially different economic sectors, which complicates direct comparison of the effects achieved. Furthermore, the two-year observation period is insufficient to evaluate the long-term impact of digitalising medical examinations on employee morbidity and occupational risk — effects in this domain typically manifest over a 5–7 year horizon.

Conclusion

The research conducted permits the following scientifically significant conclusions to be drawn.

First, the developed three-layer IT architecture of the medical examination management system, grounded in microservices design principles and integrated with HR and governmental medical information systems, provides a fundamentally superior level of functionality, scalability and operational reliability compared with monolithic solutions and traditional paper-based systems. The microservices approach should be regarded as the design standard for such systems under contemporary conditions.

Second, the validation of the system on a representative sample of organisations in the Republic of Uzbekistan confirmed its high operational and economic effectiveness. Statistically significant reductions in time costs (-71.2% , $p < 0.001$), a reduction in administrative expenditure (-65.8% , $p < 0.01$) and an ROI of 218% in the second year of operation attest to the project's strong investment attractiveness. A payback period of 14.2 months makes implementation economically justifiable even under conditions of limited investment budgets.

Third, the quality of employee health monitoring increases substantially upon transition to the digital system: the share of timely detected health deviations rose by 37.3 percentage points. This demonstrates that the economic effectiveness of digitalising medical examinations is not confined to operational savings — it also encompasses a social benefit in the form of a genuine improvement in personnel health protection.

Fourth, the pace and completeness of positive effect achievement depend substantially on the organisation's level of digital maturity. This necessitates the inclusion of digital maturity diagnostics as a mandatory preliminary stage in any medical examination management system implementation project.

Fifth, the proposed model has the potential to be scaled to the level of national policy: if implemented on a centralised platform for organisations of the Republic of Uzbekistan, the total economic effect from reduced administrative burden and improved medical monitoring is estimated by the authors at more than 200 billion UZS per year.

Directions for further research include the development of an adaptive system version for small enterprises, longitudinal study of the impact of digitalising medical examinations on occupational morbidity and labour productivity, the creation of predictive algorithms for assessing personnel health based on accumulated data, and the methodological development of instruments for evaluating the strategic and intangible effects of IT investments in the social sector.

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