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Reviewers:

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Heorhii Kuchuk – Dr. Sc. (Engineering), Professor, Professor of the Department of Computer Engineering and Programming, National Technical University "Kharkiv Polytechnic Institute".

Authors: Artiukh R., Baryshevskyi A., Bazilevych K., Bilousov M., Bulavin D., Bushuyev S., Chernov S., Chumachenko D., Chumachenko I., Chumachenko T., Dotsenko N., Fedorovich O., Husieva Yu., Khovrat A., Kobziev V., Kosenko N., Kosenko V., Kozyr S., Kritskiy D., Kryvokoritov A., Leshchenko Yu., Malyeyeva O., Meniailov Ie., Molokanova V., Nekrasov I., Nevliudova V., Parfeniuk Yu., Polianskyi A., Popov A., Popova O., Prokhorov O., Shybanov S., Starodubcev M.

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INFORMATION SUPPORT ARCHITECTURE FOR IMPLEMENTING POPULATION BIOSAFETY PROGRAMS DURING EMERGENCIES

Chumachenko D., Meniailov Ie., Bazilevych K., Parfeniuk Yu., Chumachenko T.

Emergencies increase the risk of infectious diseases while simultaneously disrupting healthcare delivery, surveillance, infrastructure, and interorganizational coordination. This chapter develops a conceptual information-support architecture for implementing population biosafety programs through a project office. The proposed architecture integrates epidemiological, clinical, laboratory, environmental, resource, and project-management information within six functional layers: data sources, acquisition and interoperability, integrated data management, analytics, decision and program coordination, and information presentation. Governance, security, data quality, traceability, and feedback are considered cross-cutting requirements. The biosafety project office is positioned as an institutional interface that translates multidisciplinary evidence into program priorities, resource allocation, coordinated actions, and implementation monitoring. The chapter demonstrates that effective information support depends not only on technical integration but also on clearly assigned responsibilities, common standards, interorganizational cooperation, qualified personnel, and transparent communication of uncertainty. The architecture provides a reference model for connecting changes in epidemiological risk with accountable and adaptive program decisions during emergencies.

1. Introduction

Emergencies, including armed conflicts, natural disasters, population displacement, infrastructure disruption, and disease outbreaks, can substantially increase the risk of infectious disease transmission. They may damage water and sanitation systems, interrupt healthcare delivery, constrain laboratory capacity, disrupt supply chains, and weaken epidemiological surveillance. Evidence indicates that insufficient preparedness, fragmented coordination, and inadequate monitoring intensify the consequences of public health emergencies, whereas multisectoral cooperation, integrated services, and digital surveillance strengthen health system resilience [1]. Under such conditions, population biosafety depends not only on collecting epidemiological data but also on the institutional capacity to transform incomplete, heterogeneous, and rapidly changing information into timely and coordinated decisions.

Integrated disease surveillance provides the foundation for this process by connecting information across diseases, institutions, administrative levels, and sectors. However, its global implementation remains uneven because of fragmented

information systems, insufficient resources, unclear institutional responsibilities, and incomplete governance arrangements [2]. Assessments of health information systems in eight European countries also identified organizational, technical, legal, and resource-related limitations, including inadequate interoperability, inconsistent definitions, manual data processing, and weak data-sharing mechanisms [3]. Therefore, effective information support requires not only digital infrastructure but also standardized data, defined responsibilities, qualified personnel, and sustainable interorganizational cooperation.

In emergencies, epidemiological indicators must be interpreted together with information on population mobility, environmental conditions, healthcare and laboratory capacity, logistics, social vulnerability, and the characteristics of the emergency itself. Integrating these heterogeneous sources into a coherent analytical environment supports risk assessment, forecasting, early warning, and intervention evaluation, although interoperability, data quality, privacy, and ethical governance remain significant challenges [4, 5]. A project office can provide the organizational mechanism for connecting these analytical outputs with program objectives, resources, responsibilities, and implementation activities. This role is particularly important for multidisciplinary biosafety programs comprising interdependent projects across surveillance, laboratory modeling and development, healthcare preparedness, communication, and information infrastructure.

The purpose of this chapter is to develop a conceptual information-support architecture for implementing population-biosafety programs during emergencies. The proposed approach considers the project office as an integrating layer that connects epidemiological surveillance, contextual emergency data, analytical tools, program management information, institutional responsibilities, and decision feedback. Such integration enables epidemiological changes to inform program priorities while allowing implementation results to support subsequent risk assessment, resource allocation, and corrective management decisions.

2. Information needs of a biosafety project office

The information needs of a biosafety project office are determined by its responsibility for converting scientific evidence and operational data into coordinated program decisions. These needs exist at three interconnected levels. At the strategic level, information is required to assess whether the program remains aligned with population biosafety priorities and anticipated emergency scenarios. At the tactical level, the project office needs evidence to prioritize projects, allocate resources, manage interdependencies, and select corrective actions. At the operational level,

it requires timely information on activities, milestones, deliverables, emerging constraints, and deviations from approved plans. The information environment must therefore integrate epidemiological intelligence with program management data rather than maintaining them as separate analytical and administrative domains.

The first information domain concerns the current and anticipated biosafety situation. It includes infectious disease incidence and prevalence, mortality, hospitalization, laboratory confirmed cases, syndromic indicators, pathogen characteristics, vaccination coverage, population mobility, environmental conditions, healthcare capacity, and the location of vulnerable groups. During emergencies, these data should be supplemented with information on infrastructure damage, disruptions to water and sanitation services, displacement, access to healthcare, supply chain disruptions, and the availability of medical countermeasures. Integrated surveillance is particularly important because fragmented sectoral systems may produce incomplete or inconsistent assessments of a developing threat [2]. The project office requires not only current indicator values but also trends, geographic distributions, forecasts, alert thresholds, data quality assessments, and explicit descriptions of analytical uncertainty. This information supports situational awareness and enables program priorities to be adjusted as the epidemiological context changes.

The second domain comprises information on program implementation. For each project, the office should maintain structured data on objectives, expected results, responsible organizations, schedules, milestones, budgets, personnel, infrastructure, procurement, dependencies, risks, issues, and implementation status. Consolidating these data at the program level enables identification of competing resource requirements, delayed activities, critical dependencies, and projects whose outputs are essential to other components of the biosafety system. Information on project performance should be connected to biosafety outcomes; completion of a technical activity is insufficient if it does not improve surveillance coverage, laboratory readiness, response time, or decision quality. Research on project management in healthcare emphasizes that organizational alignment, governance, management competence, personnel capacity, and resource availability are central to effective project implementation [6]. Accordingly, the project office needs information that supports both administrative control and assessment of the practical value created by program activities.

The third domain concerns governance, coordination, and accountability. A multidisciplinary biosafety program involves public health authorities, healthcare institutions, laboratories, emergency services, local administrations, research organizations, and other data providers. The project office, therefore, requires

an up-to-date stakeholder register, clearly assigned responsibilities, data ownership and access rules, information-sharing procedures, escalation paths, and records of interorganizational decisions. Evidence from European health information system assessments demonstrates that unclear responsibilities, inconsistent standards, insufficient interoperability, and legal uncertainty regarding data exchange can materially restrict emergency preparedness [3]. Each information product should consequently contain metadata describing its source, reporting period, validation status, responsible institution, processing methods, limitations, and permitted uses. Maintaining an auditable connection among source data, analytical outputs, management decisions, and assigned actions is necessary for accountability and to prevent conflicting interpretations across participating organizations.

Finally, the project office needs information that supports institutional learning and adaptive management. This includes decision logs, risk registers, records of assumptions, lessons learned, evaluation findings, corrective actions, and explanations of why particular interventions were selected or rejected. Health emergency management depends on both explicit knowledge contained in datasets and procedures and tacit knowledge accumulated by analysts, managers, and responders; failure to preserve the latter weakens continuity between successive emergencies [7]. Information should therefore be presented in role-specific and decision-oriented formats: strategic summaries for program leadership, risk and dependency views for project managers, epidemiological dashboards for analysts, and action registers for implementing organizations. The effectiveness of information support should ultimately be assessed by whether it improves the timeliness, consistency, traceability, and adaptability of biosafety program decisions rather than by the quantity of data collected.

3. Sources and categories of information

The information environment of a biosafety project office should combine data describing the epidemiological situation, emergency context, health system capacity, and program implementation. Information categories specify what must be known for decision-making, whereas information sources identify the institutions and systems from which these data originate. Sources may be primary, such as laboratory reports and field assessments; administrative, such as hospital and procurement systems; external, such as meteorological or mobility databases; or derived, including forecasts, risk scores, and scenario analyses. Because no individual source provides a complete representation of biosafety risks, the project office must integrate

complementary data while preserving their provenance, reporting frequency, spatial resolution, and limitations.

The first category comprises epidemiological, clinical, laboratory, and genomic information. Relevant sources include national and regional surveillance systems, electronic health records, primary care and hospital databases, laboratory information systems, mortality registries, vaccination systems, syndromic surveillance, and pathogen sequencing platforms. These sources provide data on incidence, prevalence, mortality, hospitalization, symptoms, diagnostic testing, vaccination coverage, antimicrobial resistance, and pathogen characteristics. Event-based surveillance, including reports from healthcare professionals, communities, media, and specialized outbreak-monitoring platforms, may complement indicator-based systems by detecting unusual signals before they appear in routine statistics. However, surveillance data can differ in completeness, timeliness, case definitions, and geographic coverage. Global evidence shows that fragmentation between surveillance systems and sectors remains a significant barrier to integrated disease monitoring [2], while experience with the WHO COVID-19 surveillance database illustrates the importance of standardized data flows, disaggregation, curation, and transparent reporting [8].

The second category consists of contextual information required to interpret disease dynamics during an emergency. It includes demographic structure, population density, migration and displacement, transport connectivity, environmental conditions, weather, water quality, sanitation, housing, socioeconomic vulnerability, and public behavior. During armed conflicts or disasters, additional sources may include emergency service reports, infrastructure damage assessments, humanitarian information systems, satellite observations, geographic information systems, and data from local administrations and community organizations. Combining epidemiological information with social, environmental, and mobility data supports a more complete assessment of disease drivers, exposed populations, and territorial vulnerability [5]. Nevertheless, disaster-related data are frequently distributed across institutions, recorded in incompatible formats, and subject to constraints on access, maintenance, privacy, and security [4].

The third category covers health system capacity, response resources, and program implementation. Health system information includes hospital occupancy, intensive-care and isolation capacity, workforce availability, laboratory throughput, stocks of medicines and protective equipment, ambulance capacity, and continuity of essential services. It may be obtained from hospital management systems, workforce registries, logistics platforms, procurement databases, pharmaceutical information

systems, and emergency operations centers. Program information originates from project schedules, budgets, procurement plans, risk registers, issue logs, progress reports, stakeholder registers, and monitoring systems. Integrating these sources enables the project office to relate changes in epidemiological risk to available response capacity and to determine whether program activities are progressing rapidly enough to address identified threats. Assessments of European health information systems demonstrate that technical interoperability, common definitions, legislative provisions for data exchange, and adequate human resources are necessary for such integration [3].

The final category comprises analytical products and information quality metadata. Analytical products include forecasts, early-warning indicators, vulnerability maps, resource demand estimates, intervention scenarios, and evaluations of program performance. They are derived from primary and administrative data and should not be treated as direct observations. Each product should therefore be accompanied by information on its data sources, analytical method, assumptions, uncertainty, validation status, responsible institution, and intended decision context. The project office should also record completeness, accuracy, timeliness, consistency, granularity, and revision history for critical datasets. This distinction between observed data, contextual information, analytical inference, and management judgment is essential for traceable decision-making. It prevents model outputs or incomplete indicators from being interpreted as definitive evidence.

4. Conceptual information-support architecture

The proposed information-support architecture is a layered socio-technical system that connects heterogeneous data sources with analytical processes and program-management decisions. Its purpose is not to replace existing surveillance, healthcare, emergency response, or project management systems, but to integrate their relevant outputs into a coherent decision environment. The architecture comprises six functional layers: data sources, acquisition and interoperability, integrated data management, analytics, decision and program coordination, and information presentation. Governance, security, data quality, and feedback operate across all layers. A modular structure is preferable because individual components can be updated or replaced without redesigning the entire system. A recent systematic review of health information-system architectures found that layered, service-oriented, and microservice-based patterns support modularity and maintainability.

At the same time, standardized interfaces reduce integration costs and improve interoperability at the ecosystem level [9].

The data source layer incorporates the epidemiological, clinical, laboratory, genomic, environmental, demographic, infrastructure, resource, and project management sources identified in the preceding section. Data may enter the architecture as individual records, aggregated indicators, documents, spatial datasets, event notifications, or continuous data streams. Each source should be registered in a data catalog specifying its owner, purpose, update frequency, spatial and temporal resolution, access conditions, and known limitations. Source systems remain under the control of their responsible institutions; the architecture retrieves only the information required for defined biosafety and program management purposes. This approach reduces unnecessary duplication and supports distributed institutional responsibility.

The acquisition and interoperability layer provides controlled interfaces between source systems and the integrated environment. Its functions include data extraction, secure transmission, format conversion, terminology mapping, deduplication, and initial validation. Where feasible, application programming interfaces and standardized exchange formats should replace repeated manual transfer. Standards such as Fast Healthcare Interoperability Resources can support structured exchange between heterogeneous health systems. However, their successful application requires agreed profiles, terminology, and implementation rules rather than technical adoption alone [10]. The layer should accommodate both automated and manually submitted data, as emergency conditions may disrupt connectivity or require information from institutions with limited digital capacity. Validation rules should detect missing values, incompatible definitions, implausible observations, delayed reporting, and duplicate records before information proceeds to analysis.

The integrated data management layer organizes validated information into a logically coherent environment while preserving links to the sources. Depending on legal, technical, and institutional constraints, integration may be centralized, federated, or hybrid. Centralized repositories simplify analysis but may create privacy, security, and organizational risks; federated arrangements allow institutions to retain control of sensitive data but require reliable coordination and common query mechanisms. Regardless of the deployment model, the architecture should maintain metadata, version histories, data lineage records, access permissions, retention schedules, and audit logs. Health information governance encompasses the full information life cycle and requires explicit rules concerning accountability, quality,

security, access, use, archiving, and disposal [11]. Personally identifiable or sensitive information should therefore be separated from analytical datasets where possible, with access granted according to role and purpose.

The analytical layer transforms integrated data into decision-relevant evidence. Its functions may include descriptive epidemiology, spatial analysis, anomaly and signal detection, forecasting, vulnerability assessment, resource-demand estimation, scenario modeling, and evaluation of interventions. Analytical outputs should be versioned and accompanied by descriptions of the input data, methods, assumptions, uncertainties, validation status, and the appropriate scope of use. The architecture should distinguish observed indicators from model-derived estimates and management interpretations. Systematic evidence on decision-support frameworks for public health emergencies indicates that dynamic models can assist decision-making in complex settings. However, their usefulness depends on context, data availability, model transparency, and the ability to update assumptions as an emergency evolves [12]. Analytical models should consequently inform, rather than automatically determine, program decisions.

The decision and program-coordination layer connects epidemiological intelligence with project office processes. It translates alerts, forecasts, capacity estimates, and vulnerability assessments into identifiable program implications, such as the need to reprioritize projects, mobilize resources, revise schedules, initiate procurement, or escalate risks. The layer should include a consolidated program dashboard, project and dependency registers, resource and capacity views, risk and issue logs, decision records, and action-tracking mechanisms. Each decision should be linked to supporting evidence, the responsible authority, the implementation deadline, and the expected result. This creates traceability from a detected biosafety signal to the management response and subsequently to the observed implementation outcome.

The presentation and communication layer provides role-specific access to information products. Program leadership requires concise strategic summaries and exception reports; project managers need schedules, dependencies, resources, and risks; epidemiologists require detailed indicators and analytical outputs; implementing organizations need assigned actions and operational guidance. Dashboards should therefore be designed around user tasks rather than around the availability of data. Evidence from a multisite public health study shows that dashboard usability and sustained use depend on perceived usefulness, ease of interpretation, alignment with stakeholder workflows, and iterative user involvement in design [13]. Visualizations should display data currency, geographic coverage,

thresholds, uncertainty, and explanatory annotations to reduce the risk of decontextualized interpretation.

Finally, the architecture should operate as a closed information and learning cycle. Implementation results, user feedback, revised epidemiological data, and after-action findings should return to the relevant layers to update datasets, models, priorities, and procedures. Knowledge generated during an emergency should be preserved in decision logs, lessons-learned repositories, and structured action reviews. Mayigane et al. [14] emphasize that capturing experiential knowledge from early-, intra-, and after-action reviews supports continuity and timely decision-making in subsequent emergencies. Resilience should also be incorporated through backup procedures, alternative communication channels, recovery plans, and minimum offline functionality. The architecture is therefore not a static technical platform but an adaptive organizational mechanism through which evidence, decisions, actions, and learning remain continuously connected.

5. Discussion

The proposed architecture addresses a frequent separation between epidemiological analysis and program implementation. Surveillance systems and analytical models may identify emerging threats, but their practical impact remains limited if their outputs are not linked to responsibilities, resources, schedules, and corrective actions. Positioning the biosafety project office as an integrating layer creates a continuous pathway from data acquisition to analysis, management decision, implementation, and feedback. This approach is consistent with learning health system principles, according to which analytics, evidence synthesis, implementation, evaluation, and adaptation should operate as an interconnected cycle rather than as isolated functions [15]. The architecture's principal contribution is therefore both organizational and technical: it establishes traceability between changes in the biosafety situation and corresponding changes in program priorities.

Implementation will depend on institutional cooperation, not merely on the availability of digital technologies. Participating organizations must agree on responsibilities, information requirements, terminology, access conditions, reporting frequency, and escalation procedures. A technically integrated platform cannot compensate for unclear authority, incompatible workflows, or reluctance to exchange information. Qualitative evidence from emergency managers and health professionals indicates that cross-agency communication is often constrained by fragmented communication channels, inconsistent terminology, organizational boundaries, and limited understanding of other institutions' information needs [16]. Consequently,

implementation should be incremental and should begin with a limited set of high-priority decisions, critical datasets, and responsible stakeholders. Expansion should occur only after the reliability and practical value of these information flows have been demonstrated.

The architecture may improve situational awareness and coordination, but it cannot eliminate uncertainty. Emergency data may be incomplete, delayed, biased toward populations with better access to healthcare, or collected under changing definitions. Forecasts and vulnerability assessments introduce additional uncertainty related to model assumptions and data quality. A six-country study of decision-making during COVID-19 demonstrated that public health authorities simultaneously face epistemic uncertainty about the threat, strategic uncertainty about other actors' actions, and institutional uncertainty about mandates and decision-making processes [17]. Analytical outputs should therefore be presented as decision support rather than definitive instructions. Uncertainty, alternative scenarios, data limitations, and potential distributional effects should be communicated explicitly, while final accountability remains with authorized decision-makers. Excessive centralization should also be avoided because it can increase risks to privacy, cybersecurity, and operational continuity.

This chapter presents a conceptual architecture and does not empirically evaluate its performance. Its practical configuration will depend on the institutional, legal, technological, and emergency context in which a biosafety program operates. Evaluation should address more than system availability or the number of integrated datasets; relevant criteria include information timeliness, completeness, traceability, user adoption, decision latency, coordination quality, and the proportion of assigned actions implemented as intended. A recent scoping review found that evaluation of learning health-system implementation remains underdeveloped and should jointly consider stakeholders, data, research evidence, implementation processes, and socio-technical infrastructure [18]. Accordingly, the proposed architecture should be treated as a reference model that can guide context-specific design while preserving its central principle: multidisciplinary evidence creates practical value only when it is systematically linked to accountable and adaptive program action.

6. Conclusions

Effective implementation of population-biosafety programs during emergencies requires an information environment that connects epidemiological

evidence with program management processes. The proposed conceptual architecture positions the biosafety project office as an integrating mechanism linking heterogeneous data sources, analytical tools, institutional responsibilities, resources, and implementation feedback. Its layered structure supports interoperability, traceability, role-specific information delivery, and the translation of emerging biosafety risks into coordinated management actions.

The effectiveness of this architecture depends on clear information governance, common standards, reliable interorganizational exchange, qualified personnel, and explicit communication of uncertainty. Its value should be assessed not by the volume of collected data but by improvements in decision timeliness, coordination, accountability, adaptability, and program outcomes. Thus, information support should be treated as a continuous organizational capability through which multidisciplinary evidence is transformed into accountable and adaptive action in the field of population biosafety.

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