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## Section: Technical Sciences

# DEVELOPMENT OF A SYSTEM OF INDICES FOR MONITORING AND ASSESSING THE SUSTAINABILITY OF UNDERGROUND UTILITIES

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**Abstract**

The paper proposes a comprehensive system of indices to monitor and assess the operational sustainability of urban underground utility networks. Modern municipal engineering infrastructures face critical issues such as accelerating infrastructure aging, highly aggressive operating environments, and stringent financial constraints. To systematically address these challenges, this study identifies seven distinct categories of performance indices: availability, funding sources, effectiveness of rehabilitation work, accident mitigation, environmental safety, efficient use of funds, and efficiency of monitoring implementation. Each index is formalized mathematically to measure a specific operational or socio-economic dimension of utility networks. The developed methodology establishes strict regulation for calculating these indicators, determines their variations across stable intervals, and uncovers synergistic correlations between proactive organizational-technological monitoring and long-term network durability. The practical significance lies in providing municipal utility managers with a reliable decision-making framework to optimize capital investments, mitigate environmental hazards, and sustain public service provision stability.

**Keywords:** indicator, operational sustainability, indicative planning, technical condition of networks, organizational and technological monitoring.

### 1. Introduction

In contemporary urban ecosystems, the uninterrupted operation of underground utility systems serves as the primary life-support foundation for residential, industrial, and social activities. Maintaining all elements of urban engineering networks in an optimal operational state is critical to preventing sudden catastrophic failures and minimizing municipal service downtime. However, the current state of underground municipal networks is characterized by complex systemic vulnerabilities, including the accumulation of physical and moral depreciation, aggressive external operating environments, demanding soil-structure interactions, and strictly restrained public budgets. Resolving these intertwined technical and socio-economic challenges requires moving away from reactive "emergency-response" maintenance models toward proactive, long-term indicative planning backed by advanced organizational and technological monitoring systems [1].

Monitoring plays an indispensable role in tracking the historical dynamics and predicting the future trajectories of structural resources, infrastructure processes, and localized financial outcomes. Effective life-support communications require a continuous stream of metrics evaluated at predefined time intervals to identify early degradation mechanisms before they transform into large-scale accidents. For instance, detailed diagnostic data regarding the operational characteristics of wastewater disposal networks must be systematically recorded, stored, and analyzed to form the computational backbone for strategic municipal management decisions. Key operational tasks that must be explicitly governed during an integrated monitoring campaign include:

– Tracking the strict compliance of planned versus actually provided centralized wastewater disposal services in terms of total volume and quality criteria.

– Controlling the precise conformity between planned and actual physical renovation indicators of underground pipelines, including the strict adherence to scheduled preventive maintenance windows.

– Continuous real-time checking of underground structural integrity to facilitate accident mitigation during peak loading cycles.

– Ensuring absolute environmental safety by mitigating toxic emissions, preventing soil or groundwater contamination during accidental pipeline bursts, and formulating proactive risk-mitigation measures.

– Integrating state-of-the-art diagnostic equipment, remote sensing technologies, and advanced CASE-modeling platforms to oversee construction and rehabilitation projects.

– Enforcing compliance of financial indicators with projected budgets, looking specifically into the internal allocation structure and volume distribution of municipal development funds [1, 2].

A rigorous review of recent scientific literature demonstrates a growing emphasis on indicator-based evaluation tools to gauge the resilience of critical infrastructure. Prior methodologies have introduced quantitative models to capture "lifetime resilience" and failure distributions in water distribution systems. Furthermore, key performance indicators (KPIs) are widely deployed across water utility organizations to analyze mean time to repair (MTTR), service reliability, and corporate financial stability. Decision-support frameworks frequently leverage expert systems, hybrid multi-criteria approaches, and fuzzy logic to manage data uncertainties and formalize subjective expert opinions [1].

Despite these valuable advancements, prominent gaps remain unresolved within the domain of urban infrastructure management. Existing evaluation criteria remain highly inconsistent, and there is an obvious lack of an internationally unified indicator system that successfully unifies technical, financial, and environmental metrics. Most current models analyze financial performance independently of the physical degradation states of the network. Furthermore, approaches applied in foreign contexts – such as the multi-criteria composite frameworks used for evaluating economic convergence, or the hierarchy-based performance indexes designed for the Seoul

Metropolitan Subway wastewater systems–cannot be directly integrated into typical Ukrainian municipal frameworks without comprehensive structural modifications. Differences in regional infrastructure standards, historical operational contexts, and tariff regulation mechanisms demand a localized, mathematically robust system of operational indices tailored explicitly for urban underground communications [1].

## 2. Research Aim and Objectives

The primary aim of this research is to develop and formalize a comprehensive system of indices intended for the rigorous monitoring and multidimensional assessment of the operational sustainability of urban underground utilities.

To successfully achieve the stated research aim, the following targeted objectives must be systematically addressed:

1. To organize individual performance metrics into highly structured groups of indices categorized according to distinct technical, environmental, and financial criteria based on the core objectives of municipal monitoring.
2. To thoroughly examine the internal patterns of formation for each identified index and mathematically formalize the algorithmic sequence of their computation.
3. To investigate the numerical boundaries, limits of variation, and structural correlations of each index, explicitly demonstrating how specific values reflect upon the overall stability and operational safety of underground utility structures.

## 3. Research Results and Discussion

To establish a firmly formalized foundation for analyzing the operational reliability and durability of underground utilities, a comprehensive system composed of seven distinct categories of performance indices was developed. The proposed structural breakdown addresses the technical, environmental, organizational, and fiscal facets of infrastructure management, enabling indicative planning and optimal resource allocation.

### 3.1. Formalization of the Seven Index Categories

The developed system breaks down the evaluation of underground engineering utilities into the following essential categories (table 1) [1-3].

Table 1 – Structural Breakdown and Monitoring Objectives of Underground Utility Performance Indices

| No. | Index Category | Core Monitoring Objective | Operational Significance |
|---|---|---|---|
| 1 | 2 | 3 | 4 |
| 1 | Availability Index | Measures the continuous availability and quality of provided wastewater disposal or utility services. | Ensures compliance with state standards and consumer service level agreements (SLAs). |
| 2 | Funding Sources Index | Analyzes the absolute volume, structural composition, and diversification of financial inputs. | Evaluates the fiscal stability of the municipal utility and its independence from volatile subsidies. |
| 3 | Effectiveness of Rehabilitation Work | Compares the physical scope and quality of completed pipeline renovations against initial targets. | Measures the productivity of repair crews and the quality of new infrastructure materials. |

Table 1 (concluded)

| 1 | 2 | 3 | 4 |
|---|---|---|---|
| 4 | Accident Mitigation Index | Tracks the reduction in systemic failure rates, burst frequencies, and unexpected downtime. | Reflects the direct impact of predictive and preventive maintenance strategies. |
| 5 | Environmental Safety Index | Quantifies the prevention of hazardous emissions, groundwater contamination, and ecologic damage. | Ensures strict compliance with environmental protection regulations. |
| 6 | Efficient Use of Funds Index | Evaluates the cost-efficiency per linear unit of pipeline renovation or emergency repair. | Optimizes the internal structure of capital expenditure (CapEx) and operational expenditure (OpEx). |
| 7 | Efficiency of Monitoring Implementation | Assesses the accuracy, timeliness, and technical coverage of the deployed tracking networks. | Measures the operational return on modern diagnostic equipment and remote sensing tools. |

**3.2. Methodological Calculation and Numerical Limits**

The mathematical formalization of these indices mandates the standardization of heterogeneous input parameters into dimensionless coefficients varying within strictly regulated intervals. Each index is structured to yield values between 0.0 (critical, highly unstable state) and 1.0 (optimal, fully sustainable operation). The calculation methodology relies on tracking the absolute and relative deviations of monitored structural, process, and outcome parameters from their historical and targeted baselines [1, 4].

For example, the Accident Mitigation Index is formulated by evaluating the historical frequency of emergency pipe interventions over a given time interval against the current reporting cycle, normalized by the total network length. If the rate of degradation decelerates due to strategic preventive relining, the index trends toward 1.0. Conversely, if sudden pipeline bursts multiply due to deferring maintenance, the index falls past predefined threshold values, triggering an automated emergency warning within the management framework [1, 5].

The Effectiveness of Rehabilitation Work Index utilizes ratios comparing the total length of successfully modernized network segments against the total length of pipelines officially designated as critically depreciated or physically exhausted. By analyzing the mathematical correlations between these seven categories, the framework demonstrates a clear synergetic interaction: higher values within the Efficiency of Monitoring Implementation Index directly correspond to accelerated scores in Accident Mitigation and more optimized vectors in the Efficient Use of Funds Index [1, 5].

**3.3. Management Implications for Municipal Enterprises**

The proposed framework serves as an actionable managerial toolkit for the executive directors and chief engineers of municipal utility enterprises. Instead of managing assets based on arbitrary political pressures or purely historical conventions, administrators can execute data-driven, grounded management decisions. The indicative limits set by this methodology provide a transparent mechanism to argue for capital budget expansions before city councils, since a clear decline across the Availability or Environmental Safety indices provides unassailable quantitative evidence of structural risks [1].

## 4. Conclusions

The research successfully establishes a rigorous, unified system of indices tailored for monitoring and evaluating the operational sustainability of urban underground utilities. By partitioning performance metrics into seven distinct yet mathematically intertwined categories, the framework bridges the long-standing gap between technical degradation analysis and fiscal planning. The formalization of these indicators enables municipal enterprises to shift toward predictive infrastructure planning, thereby maximizing the efficiency of reconstruction strategies, optimizing scarce capital allocation, and lowering the systemic risks associated with aging engineering networks. Ultimately, implementing this indicator framework significantly elevates the quality of urban infrastructure management, guaranteeing the long-term stability of vital public services.

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