ANALYSIS OF OPERATIONAL PARAMETERS IN A MUNICIPAL LANDFILL - CASE STUDY

B. IVAN - National University of Science and Technology POLITEHNICA Bucharest, Bucharest, Romania, bogdan.ivan0611@gmail.com
O.R. CHIVU - National University of Science and Technology POLITEHNICA Bucharest, Bucharest, Romania
C. BORDA, National University of Science and Technology POLITEHNICA Bucharest, Bucharest, Romania
M. GHEORGHE - National University of Science and Technology POLITEHNICA Bucharest, Bucharest, Romania
M. ZAMFIR - National University of Science and Technology POLITEHNICA Bucharest, Bucharest, Romania
A.Ş. IACOB - National University of Science and Technology POLITEHNICA Bucharest, Bucharest, Romania

Abstract: *This paper presents an integrated analysis of the operational parameters in a municipal solid waste landfill, based on a representative case study. Unlike traditional approaches that address waste management processes separately, this study investigates the interdependence between key operational variables, including leachate level and flow, biogas production, internal temperature, waste density, and slope stability. A mathematical modelling framework is developed to describe the relationships between biological, hydraulic and mechanical processes that take place within the landfill. The results highlight significant seasonal variations, showing that the increase in temperature increases biogas production, but also leads to greater leachate generation and accumulation. This, in turn, negatively affects the stability of the slope due to increased pore pressure. The study reveals a critical trade-off between operational performance and structural safety, highlighting the need for integrated monitoring and control of waste management processes. A synthetic performance indicator is proposed to assess the overall behavior of the system and identify critical operating conditions. The findings contribute to a better understanding of landfill dynamics and provide practical support for optimising operational strategies, improving environmental protection and reducing risks associated with landfill operation*.
Keywords: municipal landfill; operational parameters; leachate; biogas; slope stability; mathematical modelling; performance indicator; waste management

1. INTRODUCTION

Municipal landfill management is an essential component of modern waste management systems, being the last link in the disposal flow and, at the same time, a complex technological system with direct implications for the environment and operational safety. In contrast to traditional approaches, which treat storage as a passive storage structure, recent research highlights its dynamic character, driven by interdependent physical, chemical and biological processes, which are constantly evolving.

In current operation, the landfill functions as an operational system in which parameters such as leachate level, biogas production, internal temperature, degree of compaction or mechanical stability of the waste mass are closely correlated. The variability of these parameters directly influences the overall performance of the warehouse, both from a technical point of view and from the perspective of environmental impact. However, in the literature, most studies approach these processes in isolation, without sufficiently highlighting the interdependencies between them and the cumulative effects on the functioning of the system.

This lack of integration leads, in practice, to difficulties in optimising the operation of landfills, in particular in terms of leachate control, biogas capture efficiency and maintenance of structural stability. For example, increasing leachate levels can generate additional pressures in the waste mass, affecting the stability of slopes, while temperature variations can influence biological processes and the properties of insulation materials. Similarly, the degree of compaction influences both the permeability and the rate of gas generation, highlighting the need for an integrated approach in the analysis of operational parameters.

In this context, it becomes necessary to develop analysis models that allow the simultaneous evaluation of the main operating parameters and the identification of the functional relationships between them. Such an approach facilitates the understanding of the real behavior of the warehouse and allows the substantiation of optimization strategies based on relevant technical data.

The present paper aims to analyze the essential operational parameters in a municipal landfill, using a representative case study. The main objective is to identify the correlations between the operating parameters and to evaluate their influence on the performance of the system. In this regard, variables such as the level and flow rate of leachate, biogas production, internal temperature and mechanical stability indicators are analyzed, in order to develop an integrated evaluation framework.

Through this approach, the article contributes to the transition from a descriptive analysis of landfills to an operational and predictive one, providing useful tools for optimizing their operation. The results achieved can support both warehouse operators and decision-makers in order to increase efficiency, reduce risks and align with current requirements on environmental protection and sustainable development.

2. METHODOLOGY

The proposed methodology is based on the integrated analysis of the main operational parameters of a municipal landfill, considered as a dynamic system, characterized by complex interactions between hydraulic, biological and mechanical processes. The aim is to identify the functional relationships between the parameters and to assess their impact on the overall performance of the repository.

The analysis is carried out on the basis of a case study, using measured or estimated operational data, and involves three main steps: definition of the relevant parameters; mathematical modeling of processes; evaluation of the correlations and performance of the system.

The following main parameters were taken into account in the study:

- L leachate level (m)
- Ql leachate flow rate (m^3/day)
- Qg biogas flow rate (Nm^3/h)
- T temperature in waste mass (°C)
- ρ density of compacted waste (t/m^3)
- FS slope safety factor (-)

These parameters were selected due to the direct influence on geotechnical stability, the efficiency of biological processes and the risk of pollution.

Biogas production is modeled using a kinetic relationship of the first order:

$$Q_{g(t)} = k * VS * e^{-t/\tau} \quad (1)$$

where:
k – biological degradation coefficient (1/year)
VS – volatile organic matter content (kg)
t – time (years)
τ – the time constant of the process

The level of leachate is determined by a hydraulic balance relationship, an equation that highlights the accumulation of leachate and the risk of increasing internal pressure. :

$$\frac{dL}{dt} = \frac{Q_{in} - Q_{out}}{A * n} \quad (2)$$

where: Qin – leachate flow rate generated (m^3/day)
Qout – discharged flow (m^3/day)
A – warehouse area (m^2)
n – effective porosity (-)
The stability of the slope is assessed by the safety factor:

$$FS = \frac{c + (\sigma - u) * tan\varphi}{\tau} \quad (3)$$

where: c – cohesion (kPa)
σ – normal voltage (kPa)
u – pore pressure (kPa)
φ – internal friction angle (°)
τ – shear stress (kPa)

Increasing leachate levels cause u to rise, which leads to a decrease in the safety factor.

For the overall assessment of the deposit, a synthetic indicator shall be defined:

$$PI = w1 \cdot Ln + w2 \cdot Qg, n + w3 \cdot FSn + w4 \cdot Tn \quad (4)$$

where: PI – performance indicator
- WI – weighting coefficients
- n-index – normalized values

Data analysis is performed by linear and nonlinear regression, sensitivity analysis and multicriteria evaluation. The goal is to determine the influence of each parameter on the overall performance and to identify critical operating thresholds.

3. RESULTS AND DISCUSSIONS

For the case study, a municipal warehouse with active operation was considered, and the operational parameters were measured for a monitoring period of 12 months.

The analyzed municipal landfill is located outside the built-up area of city X, at a distance of about 8 km from the center of the locality, on a land with a total area of 32ha. The facility is designed for a total capacity of 2,400,000 m3 of waste and has been operating for 20 years. The deposit is of the cell type, with typified explatation. The site is located in an area with a weak undulating relief, an average slope of less than 3%, at an altitude of 226-232m above sea level. The cover layer consists of dusty clays with low permeability, over which sandy formations follow.

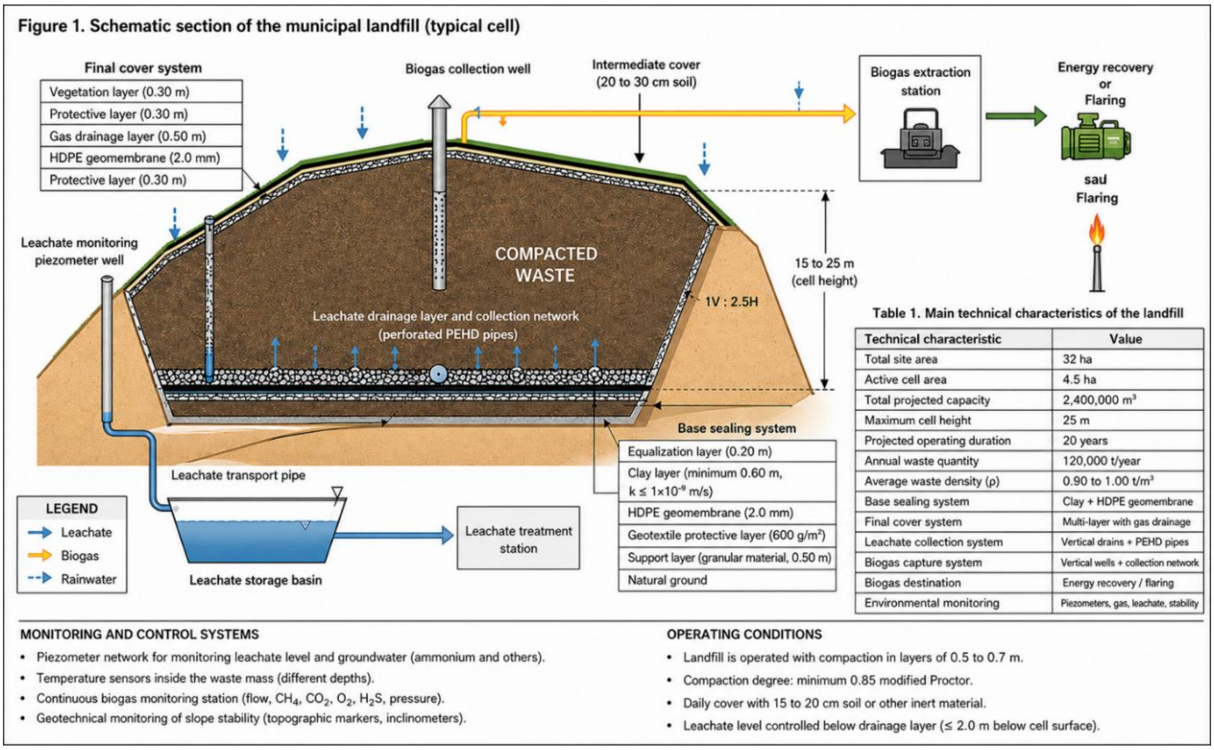

Figure 1. Technical diagram of the structure and operation of a municipal landfill

The analyzed municipal landfill is a compliant facility, designed and operated in accordance with the technical and environmental requirements specific to the management of municipal solid waste. It is located in a peri-urban area, on a land with favorable geotechnical conditions, characterized by low permeability and adequate natural stability. From a constructive point of view, the warehouse is organized on successive storage cells, operated in stages, each cell being provided with isolation systems at the base and sides. The sealing system is composite and includes a layer of compacted clay with low permeability ($k \leq 1\times10^{-9}$ m/s), over which a high-density polyethylene (HDPE) geomembrane is installed. This system ensures the prevention of leachate infiltration into the soil and the protection of groundwater.

For leachate management, the landfill is equipped with a drainage system consisting of a permeable granular layer and a network of perforated pipes, located at the base of the cells. The collected leachate is directed to storage tanks and then treated in dedicated facilities. The monitoring of the leachate level is carried out by means of control shafts, ensuring that it is kept below the permitted limits.

The biogas capture system consists of vertical wells and networks of collector pipes, connected to an extraction station. The gas resulting from the anaerobic degradation processes is extracted in a controlled manner and can be used for energy or burned in a flare, depending on the configuration of the installation. Regulating the pressure and monitoring the gas composition are essential for the efficient operation of the system.

The warehouse is also equipped with a daily and intermediate covering system, made of inert materials or soil, to limit gas emissions, odors and water infiltrations. At the end of operation, the cells are closed by a multilayer final coating system, which includes waterproofing, drainage and topsoil layers, ensuring integration into the environment.

From an operational point of view, the activity of the landfill involves the reception of waste, its distribution on the active surface, mechanical compaction and modeling of slopes. The degree of compaction is controlled to optimize the use of available volume and ensure structural stability. Continuous monitoring of operational parameters, such as leachate level, internal temperature, biogas production and slope stability, allows real-time evaluation of system performance.

Overall, the analyzed warehouse functions as an integrated technological system, in which the construction components and operational processes are interconnected, with the main objective of minimizing the impact on the environment and ensuring a safe and efficient operation.

Table 1. Operational parameters of the urban warehouse

Moon	L (m)	Ql (m^3/day)	Hg (Nm^3/h)	T (°C)	ρ (t/m^3)	FS
Ian	1.2	45	320	32	0.85	1.45
Feb	1.3	48	340	34	0.86	1.42
Mar	1.5	55	380	36	0.88	1.38
Apr	1.7	62	420	40	0.90	1.32
May	1.9	70	460	44	0.92	1.28
Jun	2.1	78	500	48	0.95	1.22
Jul	2.3	85	540	52	0.97	1.18
Aug	2.4	88	560	54	0.98	1.15
Sep	2.2	80	530	50	0.96	1.20
Oct	2.0	72	490	46	0.94	1.25
Nov	1.8	65	450	42	0.91	1.30
Dec	1.5	58	400	38	0.89	1.35

Leachate level (L)

A progressive increase in the leachate level is observed between March and August, reaching a maximum of **2.4 m**. This evolution is correlated with the increase in temperature, the intensification of biological processes, the increase in leachate flow. After this period, the level decreases due to reduced rainfall, increased drainage efficiency.

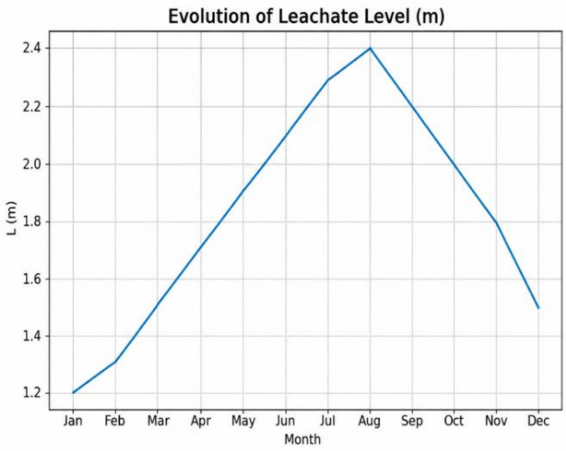

Figure 2. Evolution of leachate level in the repository

Exceeding the 2 m threshold indicates an increased risk of instability and high interstitial pressure. Leachate flow (Ql) values increase from 45 m^3/day to 88 m^3/day, indicating an intensification of organic degradation and an increase in internal liquid production. A direct correlation is observed:

$$L\uparrow \Rightarrow Ql\uparrow \quad (5)$$

Biogas production (Qg)

A significant increase to **560 Nm³/h** is observed in the summer months. This confirms intense biological activity and optimal conditions (T = 50–55°C). After August, production decreases, which leads to a reduction in temperature and humidity.

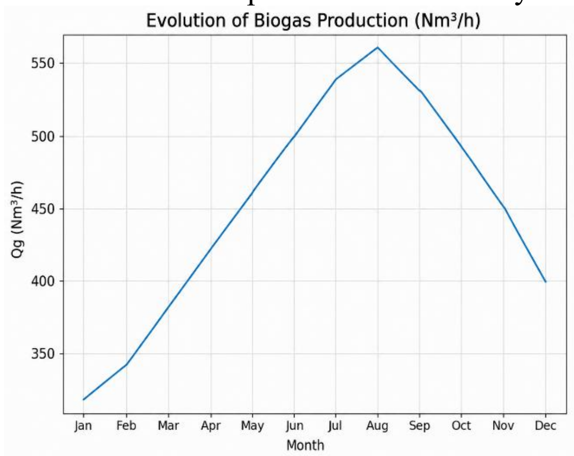

Figure 3. Evolution of biogas production as a function of time

Temperature (T)

The temperature increases from 32°C → 54°C, which indicates the transition to the thermophilic regime, with the mention that exceeding 50°C leads to the risk of degradation of the liner and drying of the clay.

Density (ρ)

It increases progressively due to continuous compaction and natural compaction. This has the impact of decreasing permeability and negatively influencing the leachate and gas.

The comparative analysis highlights a direct correlation between internal temperature, biogas production and leachate generation. The increase in temperature causes biological processes to accelerate, which leads to a simultaneous increase in gas production and the amount of leachate. This interdependence confirms the dynamic nature of the warehouse and the need for integrated monitoring of operational parameters.

Safety Factor (FS)

The safety factor (FS) registers a significant decrease from 1.45 to 1.15, which indicates a progressive degradation of the slope stability as the internal conditions of the deposit change. The increase in the leachate level causes the interstitial pressure (uuu) to increase, which leads to the reduction of the effective stresses and implicitly to the decrease of the FS, and reaching values below 1.2 signals the appearance of a real risk of instability.

Performance Indicator (PI)

The performance indicator (PI) reflects seasonal variations in the operation of the warehouse, highlighting a progressive decrease towards the summer months, when the system is subject to the most demanding conditions. The minimum value recorded in August (PI = 0.58) indicates a critical period, characterized by high temperatures, intense biogas production and increased leachate levels, factors that negatively affect stability.

In contrast, the higher values of the indicator in the winter period (PI = 0.72 in January and 0.70 in December) reflect more stable operating conditions, determined by the reduction of biological activity and leachate accumulation. Thus, the IP indicator clearly highlights the trade-off between the efficiency of biological processes and the structural safety of the repository, being a useful tool for identifying critical periods of operation.

Table 2. Seasonal variation of the performance indicator

Moon	**PI**
Ian	0.72
Apr	0.68
Jul	0.60
Aug	0.58
Dec	0.70

The analysis of the operational parameters highlights the complex and interdependent nature of the processes that take place inside the landfill. The results obtained confirm that seasonal variations significantly influence the behavior of the system, both biologically and geotechnically.

A first relevant aspect is the direct correlation between temperature and biogas production. The maximum values of the biogas flow recorded in the summer period are associated with high temperatures (above 50°C), which indicates the transition to a thermophilic regime of biological processes. This behavior is consistent with studies in the literature, which show that the activity of methanogenic microorganisms is optimal in the range of 35–55°C. However, although these conditions favor the increase of biogas production, they can generate additional risks, such as degradation of insulation materials or changes in the mechanical properties of the waste mass. As regards leaching, the results indicate a simultaneous increase in level and flow during periods of intense biological activity. This evolution is determined both by the decomposition of organic matter and by the intake of water from precipitation. The observed correlation between the leachate level and the safety factor confirms that the accumulation of liquid in the waste mass leads to an increase in the pore pressure, which reduces the shear resistance and implicitly the stability of the slopes. The decrease in the value of the safety factor below the threshold of 1.2, recorded during the critical period, indicates the existence of a real risk of instability, an aspect also signaled in other studies on the behavior of deposits under conditions of partial saturation.

Another important element is the influence of waste density on the analyzed parameters. Increasing the degree of compaction causes the permeability to be reduced, which can lead to the accumulation of leachate and an increase in internal pressure. At the same time, compaction favors the approximation of particles and the creation of more efficient conditions for biological processes, indirectly contributing to the increase of biogas production. This dual effect highlights the need to optimise the compaction process so as to achieve a balance between biological efficiency and structural safety.

The results achieved underline the existence of a trade-off between operational performance and system stability. During periods of intense biological activity, the landfill achieves a high level of efficiency in terms of biogas production and degradation of organic matter, but this is accompanied by an increase in the risks associated with leachate and mechanical stability. In contrast, during cold periods, although stability is higher, biological processes are slower, which reduces the overall efficiency of the system.

Compared to the classic approaches in the literature, which deal separately with hydraulic, biological or mechanical processes, the results of this study highlight the importance of an integrated analysis of operational parameters. The proposed model allows the identification of critical relationships between variables and provides a basis for the development of optimization strategies adapted to the real operating conditions. Also, the use of the operational performance indicator (IP) allows a synthetic assessment of the condition of the warehouse and the highlighting of critical periods of operation. The minimum values of this indicator coincide with the ranges in which the leachate level and temperature reach maximum values, and the stability is reduced, confirming the validity of the proposed method.

In conclusion, the analysis carried out demonstrates that the efficient management of a landfill cannot be achieved through individual control of the parameters, but requires an integrated approach, based on continuous monitoring and correlation of them. The results obtained can be an important support for operational optimization and risk reduction associated with the operation of municipal landfills.

4. CONCLUSIONS

The analysis of operational parameters in a municipal landfill highlights the complex and dynamic character of this system, in which biological, hydraulic and mechanical processes are closely interdependent. The results obtained demonstrate that seasonal variations significantly influence the behavior of the deposit, generating simultaneous changes in leachate level, biogas production, internal temperature and structural stability.

A key aspect highlighted by the study is the direct correlation between temperature and biogas production. The increase in internal temperature favors the activity of methanogenic microorganisms, leading to an intensification of organic matter degradation processes and a significant increase in biogas flow. This evolution indicates a high biological efficiency of the system, especially in hot periods, but also involves associated risks, such as overheating of the waste mass or degradation of insulation materials.

At the same time, the results show that the intensification of biological processes is accompanied by an increase in the flow rate and level of leachate. The accumulation of leachate in the waste mass causes the interstitial pressure to increase, which negatively influences the mechanical stability of the deposit. The decrease in the value of the safety factor during critical periods confirms that the leachate level is one of the most important control parameters in the operation of landfills. Exceeding certain thresholds can lead to the emergence of instability phenomena, with major implications for operational safety and the environment.

Another important result is the influence of waste density on the overall behavior of the system. Increasing the degree of compaction contributes to the reduction of air volume and the optimization of biological processes, but, at the same time, it reduces permeability and favors the accumulation of leachate. This duality highlights the need for rigorous control of the compaction process so as to maintain a balance between degradation efficiency and structural safety.

The integrated analysis of the parameters made it possible to highlight a clear trade-off between operational performance and the stability of the warehouse. During periods of intense biological activity, the landfill reaches high values of biogas production, but these conditions are associated with increased leachate levels and reduced stability. In contrast, during cold periods, stability is higher, but the efficiency of biological processes is reduced. This balance between efficiency and safety is a critical aspect in landfill management.

The mathematical model proposed in the paper allows the description of the functional relationships between the analyzed parameters and provides a useful tool for evaluating the behavior of the system under different operating conditions. The introduction of the operational performance indicator (IP) is a novelty, facilitating a synthetic assessment of the condition of the repository and the rapid identification of critical periods. This indicator can be used as a decision-support tool in warehouse management, helping to optimize processes and reduce risks. The results achieved underline the importance of continuous monitoring of operational parameters and the use of integrated analysis systems. The implementation of modern monitoring technologies, such as real-time sensors and data analysis systems, can significantly improve the control and reaction capacity of operators. In this context, landfill can no longer be considered a passive system, but must be approached as an active system, which requires continuous and adaptive management.

In conclusion, the study demonstrates that the optimization of the operation of municipal landfills must be based on an integrated approach, which takes into account the interdependence of operational parameters. By using mathematical models and synthetic indicators, effective solutions can be identified to increase performance and reduce environmental impact. Future research directions should aim at developing advanced predictive models, integrating artificial intelligence into operational data analysis, and expanding long-term studies to validate results in real operating conditions.

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