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Indexing in Scopus and Web of Science ensures high international visibility of publications, promotes citation growth, and reflects the editorial board's commitment to publishing relevant, original, and scientifically significant research in the fields of geology and technical sciences.

«Қазақстан Республикасы Ұлттық ғылым академиясының Хабарлары. Геология және техникалық ғылымдар сериясы» ғылыми журналы 2016 жылдан бастап халықаралық реферативтік және ғылымиметриялық Scopus дерекқорында индекстеледі және тұрақты библиометриялық көрсеткіштерді көрсетіп келеді.

Сонымен қатар журнал Web of Science платформасының (Clarivate Analytics, 2018) халықаралық реферативтік және наукометриялық дерекқоры Emerging Sources Citation Index (ESCI) тізіміне енгізілген.

ESCI дерекқорында индекстелуі журналдың халықаралық ғылыми рецензиялау талаптары мен редакциялық этика стандарттарына сәйкестігін растайды, сондай-ақ Clarivate Analytics компаниясы тарапынан басылмды Science Citation Index Expanded (SCIE), Social Sciences Citation Index (SSCI) және Arts & Humanities Citation Index (AHCI) дерекқорларына енгізу қарастырылуда.

Scopus және Web of Science дерекқорларында индекстелуі жарияланымдардың халықаралық деңгейде жоғары сұранысқа ие болуын қамтамасыз етеді, олардың дәйексөз алу көрсеткіштерінің артуына ықпал етеді және редакциялық алқаның геология мен техникалық ғылымдар саласындағы өзекті, бірегей және ғылыми тұрғыдан маңызды зерттеулерді жариялауға ұмтылысын айқындайды.

Научный журнал «News of the National Academy of Sciences of the Republic of Kazakhstan, Series of Geology and Technical Sciences» с 2016 года индексируется в международной реферативной и наукометрической базе данных Scopus и демонстрирует стабильные библиометрические показатели.

Журнал также включён в международную реферативную и наукометрическую базу данных Emerging Sources Citation Index (ESCI) платформы Web of Science (Clarivate Analytics, 2018).

Индексирование в ESCI подтверждает соответствие журнала международным стандартам научного рецензирования и редакционной этики, а также рассматривается компанией Clarivate Analytics в рамках дальнейшего включения издания в Science Citation Index Expanded (SCIE), Social Sciences Citation Index (SSCI) и Arts & Humanities Citation Index (AHCI).

Индексирование в Scopus и Web of Science обеспечивает высокую международную востребованность публикаций, способствует росту цитируемости и подтверждает стремление редакционной коллегии публиковать актуальные, оригинальные и научно значимые исследования в области геологии и технических наук.

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INTELLIGENT DIGITAL PLATFORM FOR SOLID WASTE MANAGEMENT: SHYMKENT SMART WASTE

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Abstract. Relevance. This paper examines the theoretical and applied basis of the intelligent geoinformation platform development to improve the municipal solid waste management system of Shymkent. The study analyzed current approaches in management of the collection, transportation, sorting, and disposal of municipal wastes, and explored optimization methods based on mathematical modeling and geoinformation technologies. **Objective.** The objective of the study is to investigate the possibilities of developing an intelligent geoinformation platform for optimizing municipal solid waste management processes in Shymkent through the integration of mathematical modeling, spatial data analysis, and geoinformation technologies. **Methods.** The paper examines a multifactorial mathematical model of stochastic waste accumulation, nonlinear routing algorithms, graphical heuristic methods, and the asynchronous time management mechanism (Delta Time).

Additionally, heat map algorithms for stochastic modeling of the morphological composition of municipal solid wastes and visualization of waste distribution intensity are studied. The possibilities of processing spatial data, monitoring the condition of waste collection infrastructure, and making management decisions by using a geoinformation user interface are presented. *Results.* The combination of mathematical modeling, data analysis, and geoinformation technologies enables the automation of waste management processes, optimization of waste disposal routes, improvement of municipal service efficiency, and reduction of environmental impact. *Conclusions.* The research results can be used in the development of the intelligent information platform for household waste management in Shymkent, as well as in the creation of digital systems for managing the city's municipal infrastructure.

Keywords: municipal solid waste, geoinformation technologies, mathematical modeling, spatial analysis, intelligent platform, Shymkent Smart Waste

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ҚАТТЫ ТҰРМЫСТЫҚ ҚАЛДЫҚТАРДЫ БАСҚАРУҒА АРНАЛҒАН ИНТЕЛЛЕКТУАЛДЫ ЦИФРЛЫҚ ПЛАТФОРМА: SHYMKENT SMART WASTE

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Аннотация. *Өзектілігі.* Мақалада Шымкент қаласындағы қатты тұрмыстық қалдықтарды басқару жүйесін жетілдіруге арналған интеллектуалды геоақпараттық платформаны әзірлеудің теориялық және қолданбалы негіздері қарастырылған. Қатты тұрмыстық қалдықтарды жинау, тасымалдау, сұрыптау және кәдеге жарату процестерін басқарудың заманауи тәсілдері талданып, математикалық модельдеу мен геоақпараттық технологияларға негізделген оңтайландыру әдістері зерттелді. *Мақсаты.* Зерттеудің мақсаты – математикалық модельдеу, кеңістіктік деректерді талдау және геоақпараттық технологияларды біріктіру арқылы Шымкент қаласындағы қатты тұрмыстық қалдықтарды басқару процестерін оңтайландыруға арналған интеллектуалды геоақпараттық платформаны әзірлеу мүмкіндіктерін зерттеу. *Әдістері.* Жұмыста қалдықтардың кездейсоқ жиналуын сипаттайтын көпфакторлы математикалық модель, сызықтық емес маршруттау алгоритмдері, графтық эвристикалық әдістер және асинхронды уақытты басқару механизмі (Delta Time) қарастырылды. Сонымен қатар қатты тұрмыстық қалдықтардың морфологиялық құрамын стохастикалық модельдеуге арналған жылу картасы (Heat Map) алгоритмдері мен қалдықтардың таралу қарқындылығын визуализациялау тәсілдері зерттелді. Геоақпараттық пайдаланушы интерфейсін қолдану арқылы кеңістіктік деректерді өңдеу, қалдықтарды жинау инфрақұрылымының жай-күйін мониторингтеу және басқарушылық шешімдер қабылдау мүмкіндіктері көрсетілді. *Нәтижелері.* Математикалық модельдеу, деректерді талдау және геоақпараттық технологияларды кешенді қолдану қалдықтарды басқару процестерін автоматтандыруға, тасымалдау маршруттарын оңтайландыруға, коммуналдық қызметтердің тиімділігін арттыруға және қоршаған ортаға түсетін экологиялық жүктемені азайтуға мүмкіндік береді. *Қорытынды.* Зерттеу нәтижелері Шымкент қаласында тұрмыстық қалдықтарды басқаруға арналған интеллектуалды ақпараттық платформаны әзірлеуде, сондай-ақ қаланың коммуналдық инфрақұрылымын басқарудың цифрлық жүйелерін құруда пайдаланылуы мүмкін.

Түйін сөздер: қатты тұрмыстық қалдықтар, геоақпараттық технологиялар, математикалық модельдеу, кеңістіктік талдау, интеллектуалды платформа, Shymkent Smart Waste

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ИНТЕЛЛЕКТУАЛЬНАЯ ЦИФРОВАЯ ПЛАТФОРМА ДЛЯ УПРАВЛЕНИЯ ТВЕРДЫМИ БЫТОВЫМИ ОТХОДАМИ: SHYMKENT SMART WASTE

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Аннотация. *Актуальность.* Совершенствование системы управления твердыми коммунальными отходами является одной из актуальных задач устойчивого развития городской инфраструктуры. В условиях увеличения объемов образования отходов и усложнения логистических процессов особое значение приобретает внедрение интеллектуальных цифровых решений, основанных на математическом моделировании, пространственном анализе и геоинформационных технологиях. В исследовании рассматриваются теоретические и прикладные подходы к разработке интеллектуальной геоинформационной платформы Shymkent Smart Waste, предназначенной для совершенствования процессов сбора, транспортировки, сортировки и утилизации твердых коммунальных отходов города Шымкента. *Цель.* Исследовать возможности разработки интеллектуальной геоинформационной платформы для оптимизации управления твердыми коммунальными отходами города Шымкента путем интеграции математического моделирования, пространственного анализа данных и геоинформационных технологий. *Методы.* Методологическую основу исследования составляют многофакторное математическое моделирование стохастического накопления отходов, нелинейные алгоритмы маршрутизации, графовые

эвристические методы и механизм асинхронного управления временем (Delta Time). Рассмотрены алгоритмы построения тепловых карт (HeatMap), предназначенных для пространственной визуализации интенсивности накопления отходов. Дополнительно исследованы возможности применения геоинформационных технологий для обработки пространственных данных, мониторинга состояния инфраструктуры сбора отходов и информационной поддержки принятия управленческих решений. *Результаты.* На основе анализа математических моделей, алгоритмов маршрутизации и геоинформационных инструментов определены основные функциональные направления интеллектуальной платформы Shymkent Smart Waste. К ним относятся моделирование процессов накопления твердых коммунальных отходов, пространственная визуализация их распределения, оптимизация маршрутов транспортировки и мониторинг состояния объектов коммунальной инфраструктуры. Показано, что интеграция указанных инструментов создает предпосылки для автоматизации отдельных процессов управления отходами, повышения эффективности планирования деятельности коммунальных служб и сокращения потенциального негативного воздействия на окружающую среду. *Выводы.* Применение методов математического моделирования, пространственного анализа и геоинформационных технологий представляет перспективное направление цифровизации системы управления твердыми коммунальными отходами. Рассмотренные подходы могут быть использованы при разработке интеллектуальной платформы Shymkent Smart Waste для города Шымкента, а также при проектировании аналогичных цифровых решений для управления коммунальной инфраструктурой других городов. Практическая эффективность предложенных инструментов требует дальнейшей проверки на основе фактических данных о накоплении отходов, транспортных маршрутах и работе коммунальных служб.

Ключевые слова: твердые коммунальные отходы, геоинформационные технологии, математическое моделирование, пространственный анализ, интеллектуальная платформа, Shymkent Smart Waste

Introduction. The intelligent geographic information system (GIS) for municipal waste management is a modern information and analytical system designed to automate the collection, storage, analysis, and visualization of data related to municipal waste recycling. The main goal of a GIS is to improve waste management efficiency through the use of geographic information technologies, mathematical modeling, and data mining.

However, many GIS-based municipal solid waste management studies rely on assumed or statistically generated waste-generation parameters, while field-derived morphological and fractional composition data are not always directly incorporated into spatial routing models.

With increasing of volumes of municipal wastes and increasing the environmental

load, there is a necessity to create automated systems capable of monitoring the condition of infrastructure facilities, analyzing wastes transportation routes, predicting wastes generation, and supporting management decision-making. The use of intelligent geographic information systems can significantly improve the efficiency of municipal services and reduce the negative impact of waste on the environment (Samarskii et al., 2018; Burdenet al., 2016).

IGS combines the capabilities of geographic information systems, databases, methods of artificial intelligence and mathematical modeling. The system allows to display on the electronic map the location of container sites, wastes processing enterprises, solid wastes landfills, routes of garbage trucks and other infrastructure facilities. In addition, IGS provides processing of spatial data and analytical calculations. The main functions of the intelligent geoinformation system of solid waste management are (Sauer, 2018; Atkinson, 1989):

- storage and processing of spatial data;
- control of container sites;
- analysis of the volume of wastes accumulation;
- creation of optimal wastes disposal routes;
- forecasting of the filling of polygons;
- analysis of environmental load;
- visualization of data on the electronic card;
- support of the adoption of administrative decisions.

One of the main elements of IGS is mathematical modeling of wastes processing. Statistical and dynamic models can be used to forecast the volume of wastes. Intelligent algorithms used in IGS allow automatic analysis of large volumes of data, reveal regularities and generate recommendations for optimization of waste management systems. For example, the system can automatically identify the places of accumulation of overloaded containers, predict the need for wastes removal and choose the most effective routes for garbage trucks.

Therefore, the objective of this study was to develop and evaluate a GIS-based mathematical framework for municipal solid waste management in Shymkent using empirical field data.

Materials and Methods. *Initial data and study area.* The empirical basis of the study was formed from municipal solid waste investigations conducted in Shymkent. The studies covered four seasons and included more than 200 waste containers with a total sampled waste volume exceeding 150 m³. Waste was characterized according to 13 morphological components and 7 particle-size fractions. The study also included measurements of bulk density and moisture content. In total, more than 200 samples from 17 types of facilities were analyzed.

The morphological composition of MSW was determined from field investigations conducted in Shymkent. The analyzed waste included paper, metals, glass, plastics, polyethylene, food waste, construction waste, textile, wood, rubber and leather, and other fractions. The measured average composition is presented in Figure 1.

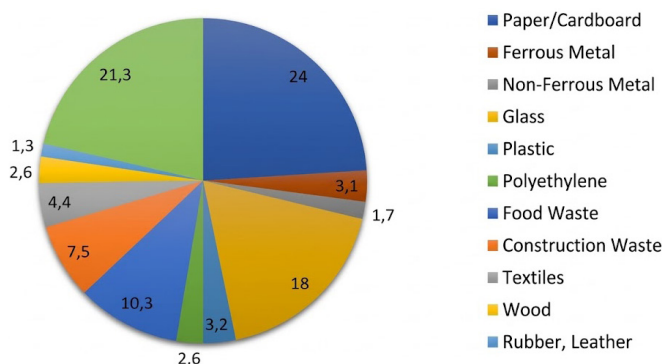


Figure 1. Morphological composition of solid household waste (on the example of the city of Shymkent).

Table 1. Fractional composition of solid household waste.

Particle-size fraction, mm	Mass fraction, %
≥ 250	1,3-2,3
250-150	5,0-22,0
150-100	12,4-22,7
100-50	21,1-29,5
< 50	30,7-50,5

The reported ranges represent the minimum and maximum mass fractions observed across the sampling periods and sites.

The intelligent geographic information system (GIS) for solid wastes management in the city of Shymkent was developed as a high-load single-page application (SPA). The key visualization and interaction element is the geographic information core, integrated by using the open-source Leaflet library (Longley et al., 2021; Chang, 2019).

The GIS prototype was implemented as a web-based interface for visualization of container locations, waste accumulation, fleet distribution and optimized collection routes.

Results and Discussions. *Multi-factor mathematical model of stochastic accumulation of residues.* The reliability and predictive value of the operation of the geoinformation system is ensured by the mathematical model of solid household waste generation. The model architecture categorically deviates from the simple linear increase in volumes used in basic modeling. Instead, a system of differential equations is used, which takes into account the stochastic (random) nature of human behavior, demographic fluctuations in population density in different areas of the Shymkent city, as well as cyclic time factors (daily, weekly and annual harmonics).

The volume of accumulated garbage $V_i(t)$ in a particular container I at any given point in Time t correction is described by a certain convolutional integral of the main waste production function multiplied by a set of nonlinear coefficients:

$$V_i(t) = V_{i,0} + \int_{t_0}^t [\Phi_i(\tau) \times K_{season}(\tau) \times K_{weather}(\tau)] d\tau \quad (1)$$

where:

$V_i(t)$ — the current volume of solid waste in container i , expressed in cubic meters (m^3) at the calculated time t .

$V_{i,0}$ — initial volume of garbage at the time t_0 (integration constant representing the waste residue after the previous incomplete discharge cycle).

$\Phi_i(\tau)$ — the main stochastic function of the intensity of garbage disposal by residents of the adjacent area (m^3/h).

$K_{season}(\tau)$ — a dimensionless seasonal macro coefficient (described by Fourier series) that regulates the amount of generation depending on the season.

$K_{weather}(\tau)$ — dimensionless micro coefficient of humidity and meteorological precipitation, which affects the hygroscopic expansion and density of waste.

τ - integration variable (virtual simulation time).

Empirical studies of solid waste logistics prove that people take out garbage unevenly: there are peaks of activity in the morning (before being sent to work) and in the evening (when returning home). For a mathematically accurate description of these vertices, the model uses the additive sum of two density functions of the normal (Gaussian) probability distribution:

$$\phi_i(\tau) = \alpha_1 \cdot \exp\left(-\frac{(\tau - \mu_1)^2}{2\sigma_1^2}\right) + \alpha_2 \cdot \exp\left(-\frac{(\tau - \mu_2)^2}{2\sigma_2^2}\right) \quad (2)$$

where: μ_1, μ_2

μ_1, μ_2 - mathematical expectations (centers) of the maximum load time on the container site.

σ_1, σ_2 - mean square deviations (standard deviations) that determine the "blurring" (Shiri) of Gaussian vertices. The larger the Sigma, the wider the dispersion, that is, the longer the population produces garbage (typical for weekends, for example).

α_1, α_2 - amplitude weight coefficients (maximum output intensity). They are directly related to the population density within a radius of 150 meters from the container coordinate. In multi-storey residential buildings (for example, "Nursat" microdistrict), the coefficients α_1, α_2 - reach maximum values.

τ - the current local time of day is in hours (in 24-hour format).

Garbage disposal patterns change radically in winter and summer. In the summer months, the consumption of melons, vegetables and containers of soft drinks in Shymkent increases sharply, which leads to an exponential increase in the mass of moist organic matter and plastic. The Fourier Series allows the GIS to establish a

perfect flat wave function that characterizes these fluctuations throughout the year without sharp programmatic "jumps" during the transition between months:

$$K_{season}(\tau) = A_0 + \sum_{k=1}^N [A_k \cos\left(\frac{2\pi k\tau}{T_{year}}\right) + B_k \sin\left(\frac{2\pi k\tau}{T_{year}}\right)] \quad (3)$$

where:

A_0 - the constant component (zero harmonics), which represents the average base value of the seasonal coefficient for a year (1.0 by default).

A_0, B_0 —the amplitude of the harmonics of the Fourier series. These parameters are calibrated based on statistical retrospective data from the city utilities (Big Data) of previous years.

k -integer index of harmonics. In the calculation kernel of the system, $N=4$ is used (accounting for semi-annual, quarterly, monthly and weekly fluctuations).

T_{year} —this is the main period of modeling, equal to the number of hours in an astronomical year (8784 hours).

Nonlinear routing and graph heuristics algorithms. One of the most complex computational tasks of the platform is the dynamic reconstruction of the routes of garbage trucks in real time. In classical performance, the calculation of the optimal routing of special equipment is reduced to the calculation of the routing of a vehicle with a limited capacity (Capacitated Vehicle Routing Problem, CVRP).

After the optimal tank cluster is rigidly attached to a particular truck, the mathematical core launches the ant Ant Colony Optimization (ACO) to find the shortest detour within the cluster. In this bioinspired algorithm, the probability that a virtual "Ant" (router search agent) will move from the current node i to the target node j at the iterative moment of time t is calculated by a complex probability model of transitions:

$$P_{i,j}^k(t) = \frac{[\tau_{i,j}(t)]^\alpha [\eta_{i,j}]^\beta}{\sum_{l \in N_i^k} [\tau_{i,l}(t)]^\alpha [\eta_{il}]^\beta} \quad (4)$$

where:

$P_{i,j}^k(t)$ — k garbage truck search algorithm the probability of the path between tanks i and j entering the last route sheet (0 to 1).

$\tau_{i,j}(t)$ —the concentration of the virtual "pheromone" at the edge of the graph between nodes i and j .

$\eta_{i,j}$ —the heuristic attraction of the string segment. This value is inversely proportional to the physical distance, which is calculated by a high-precision open-source guidance machine (OSRM).

α - the weight factor (historical memory parameter) that determines the degree of influence of the accumulated "pheromone" on path selection. at higher values of α , the algorithm tends to rely on previously created successful routes.

β - the weight factor ("greed" parameter) that determines the degree of influence of the line of sight and heuristic attractiveness. At high values of β , the algorithm always selects the nearest physical reservoir.

N_i^k - the set of all non-arrival cluster tanks that can be passed through the current point i for the k truck.

The route optimization was formulated as a capacitated vehicle routing problem (CVRP) and solved using an ant colony optimization heuristic.

In addition to morphological decomposition, the platform provides dispatchers with the most powerful spatial analysis tool — a thermal map (Heatmap), which serves to instantly visually identify the most important foci of container overflow. The heat map mechanism is fundamentally different from drawing colored circles around the coordinates of tanks. Kernel Density Estimation (KDE) was used to visualize the spatial concentration of waste accumulation and identify areas with a higher intensity of container loading.

System architecture and Geoinformation user interface. The right panel of the platform serves as a strategic command post and an analytical center (Figure 2). Architecturally, it is divided into a real-time dashboard block and a multi-tab navigation block (OpenStreetMap Foundation; QGIS Development Team, 2024; PostgreSQL Global Development Group, 2024).

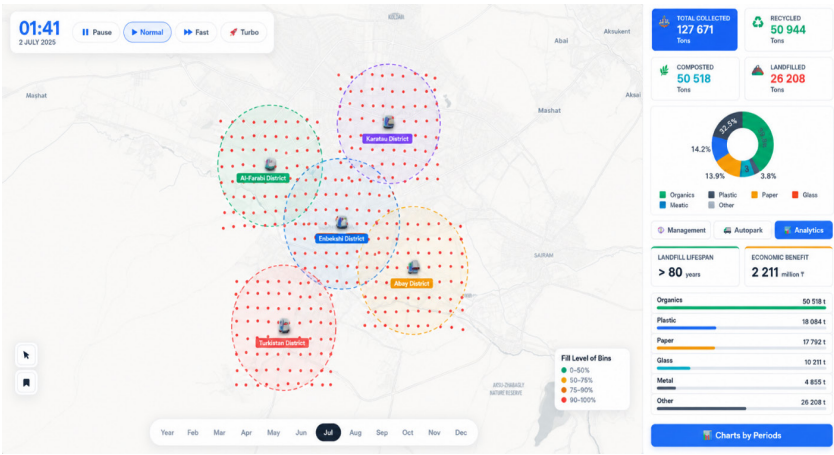


Figure 2. Intelligent geoinformation system.

At the top of the screen are four accented maps of key performance indicators. They combine data from all over the simulated city and extract common values: "general collection", "recycling", "compost" and "to landfill". Dynamic updating of these maps occurs through a unidirectional data linking mechanism, which prevents the interface from synchronizing with the simulator kernel (Figure 3).

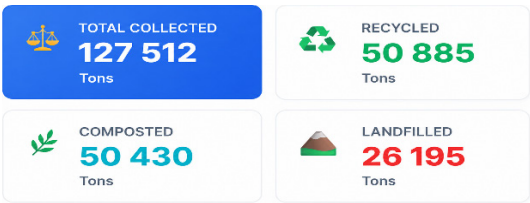


Figure 3. Performance indicators.

Directly under the dashboards is an interactive pie chart depicting the morphological (component) composition of the collected garbage (Figure 4). The system classifies waste into six main fractions: organic matter, plastic, paper, glass, metal and ash. This graphical element is displayed using the Plotly analytical library.the choice of js.Plotly.js is due to the fact that this library supports graphs in the vector format SVG (Scalable Vector Graphics), which guarantees absolute clarity of lines on monitors with high pixel density and provides interactivity when hovering the cursor.

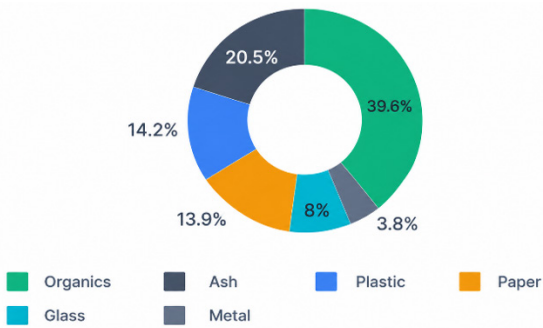


Figure 4. Interactive diagram.

The operator's infrastructure tools are grouped on three logical sub-pages: "Management", "Fleet"and "Analytics" (Figure 5). The management tab contains important Logic switches that allow you to quickly change the basic business logic of the system. The Smart Logistics switch acts as a trigger to programmatically cut off less than 75% filled containers from the target garbage truck pool and change graphical routing limits. The" base sorting "and" composting " switches dynamically change the weight coefficients in the mass distribution matrices, directing raw material flows from urban landfills to specialized processing plants.

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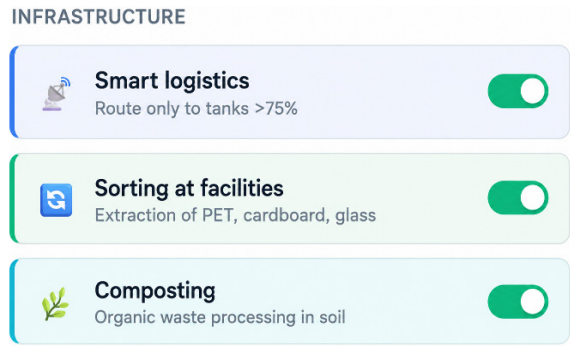


Figure 5. Infrastructure tools.

On the internal management page, a block of Fleet scaling was implemented, distributed by administrative districts (Abay, Al-Farabi, Enbekshi, Karatau, Turan) (figures 6,7). Using the simple machines add / remove buttons, the new truck in Ram will immediately install the software objects and start displaying them on the map. This operation is "fast", that is, it does not require stopping or rebooting the simulation. In addition, a filtering block is provided: the operator can completely hide the visibility and calculation logic of certain areas in order to focus computing resources and attention only on the problematic part of the city.



Figure 6. Number of fleets by District.

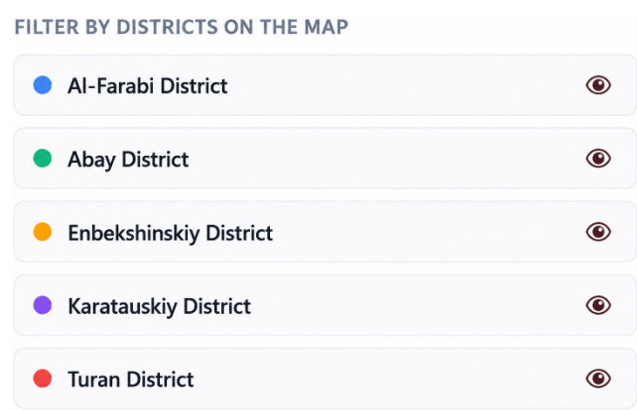


Figure 7. Filtering areas.

The inner surface of the "Fleet" is a deep telemetry control module (Figure 8). It automatically generates lists of all active machines in the system, Their Unique Identification Numbers, the degree of current occupancy of the case and the level of residual charge of the traction battery. From this section, the operator can start downloading the "efficiency report", which is displayed at the top of the main interface in the form of a modal window. In this window, the system summarizes the accumulated data for all areas, evaluates them according to the degree of logistics load and generates a performance rating of each machine based on the mathematically calculated utility effect factor (efficiency).

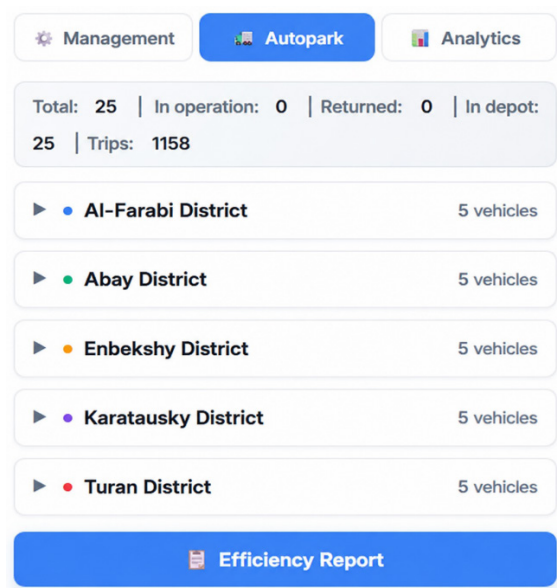


Figure 8. The inner surface of the fleet.

The analytics subpage summarizes historical and predictive data (Figure 9). The most innovative architectural solution is the built-in PDF document creation module. Unlike the vast majority of corporate systems, this platform does not use voluminous server-side document generation (Server-Side Rendering). Instead, only client-side rendering is used: the `html2canvas` library executes a Pixel snapshot of the Dom node hidden from the user with graphs (which are pre-converted from SVG to high-resolution raster PNG using the local `Plotlymethod.toImage`). After that, the `html2pdf` library asynchronously collects these images into a standardized A4 binary file, ready to be physically printed or sent for instruction.

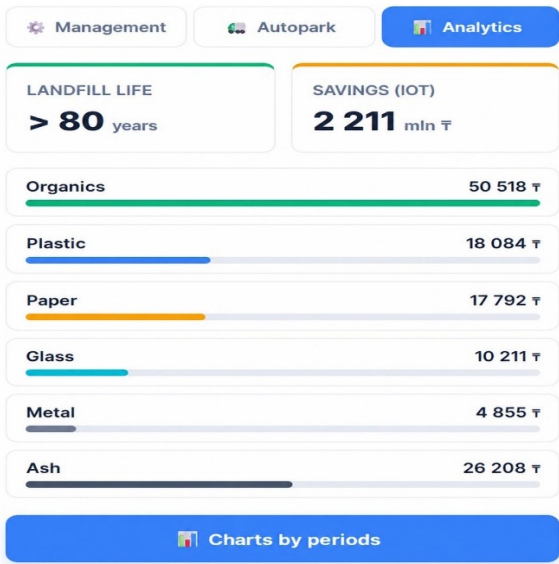


Figure 9. Analytical data.

Conclusion. This study presents an empirical-data-based approach to municipal solid waste management in Shymkent, combining field investigations, waste composition analysis, mathematical modeling, geographic information system (GIS) analysis, and collection-route optimization. Unlike approaches based primarily on synthetic or assumed waste-generation parameters, the proposed framework was developed using field data collected from the urban waste management system.

Field investigations were conducted over four seasons and included more than 200 waste containers, more than 150 m³ of municipal solid waste, and more than 200 samples collected from 17 study sites. The investigated waste was characterized according to 13 morphological components and seven particle-size fractions. These observations provided an empirical basis for describing the spatial and structural characteristics of municipal solid waste in different parts of Shymkent.

The obtained morphological and fractional composition data were used as input parameters for mathematical modeling of waste accumulation and spatial analysis. The GIS component enabled the integration and visualization of sampling locations, container sites, waste accumulation characteristics, and collection infrastructure. Spatial analysis, including heatmap-based visualization, was used to identify areas with higher concentrations of waste accumulation and to support the identification of priority collection zones.

The waste collection problem was formulated as a capacitated vehicle routing problem (CVRP), in which container locations, estimated waste volumes, vehicle capacity, and spatial distances were considered as routing constraints. An ant colony optimization (ACO) procedure was applied to obtain feasible collection routes. In this framework, the optimization algorithm is not treated as an independent simulation experiment but as a computational tool for processing field-derived spatial and waste-generation data.

The main methodological contribution of the study is the integration of empirical municipal solid waste characterization with GIS-based spatial analysis and vehicle-routing optimization. This approach establishes a direct connection between field observations, mathematical modeling, and operational waste collection planning. The resulting framework can be used to analyze spatial variations in waste accumulation, support the planning of collection operations, and evaluate alternative routing configurations.

The study also demonstrates the importance of using locally obtained waste composition and accumulation data when developing mathematical and GIS-based municipal solid waste management models. Further research should focus on expanding the monitoring network, increasing the temporal resolution of container-level observations, calibrating the accumulation model against longer-term operational data, and quantitatively validating the optimized routes under real collection conditions.

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