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Evaluation of municipal solid waste management measures in Hungary: A dynamic multilayer network framework

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ABSTRACT

The efficient management of municipal solid waste (MSW) is a complex challenge driven by increasing waste generation, evolving compositions, and ambitious European targets for sustainable development and circular economy principles. Transforming existing MSW management systems to meet future needs and facilitate the waste transition necessitates comprehensive analytical tools. This research introduces a novel dynamic multilayer network (DMN) framework for analyzing MSW management, exemplified by the Hungarian system. The DMN framework enables the exploration of cross-sectoral impacts by integrating carbon footprint life cycle assessment (LCA) indicators to evaluate greenhouse gas (GHG) emissions. We illustrate the effectiveness of policy measures through various scenarios, including enhanced organic fraction of municipal solid waste (OFMSW) source separation, implementation of a deposit–refund system (DRS), and intensified waste-to-energy (WTE) strategies. The results demonstrate that a DMN approach is a suitable methodology for governing the waste transition, supporting strategic decisions related to the development and optimization of MSW management systems in response to evolving policy and environmental goals.

1. Introduction

The evolving landscape of the circular economy (Stahel, 2016; Seyyedi et al., 2024; Aiello et al., 2025), increasingly stringent legislation (Agovino et al., 2024), and the growing volume and changing composition of municipal solid waste (MSW) (Bartelings et al., 2024; Ren et al., 2024; Kurniawan et al., 2024) present significant challenges for the municipal solid waste management sector (Katrancı et al., 2026). These trends necessitate targeted transformation and development, requiring more sophisticated analytical and optimization strategies for increasingly complex waste management systems (Al-shaikh and Abdelfatah, 2024; Alsabt et al., 2024). Countries are in urgent need of robust models and tools to rationalize their technological choices and waste management strategies (Pires et al., 2011; Aiguobarueghian et al., 2024; Mondal et al., 2026). While analyses indicate a notable increase in composting and material recycling, coupled with a decrease in landfilled waste across European countries (Shah et al., 2023), further efforts are crucial to fully achieve a circular waste economy (Weghmann, 2023). To assess the multidisciplinary effects of these policy shifts, life cycle assessment (LCA) is a promising approach, particularly for determining the carbon footprint of a system (Camana et al., 2021; Brglez et al., 2024). Research has shown that combinations of end-of-life (EoL) solutions can be evaluated from environmental, social, and economic perspectives (Mujtaba et al., 2024). Specifically, a reduction in landfilling rates, accompanied by increased composting and incineration, can significantly contribute to overall greenhouse gas (GHG) emission reduction in waste management systems (Zhao et al., 2024).

Effective policy mixes are essential, extending beyond merely selecting end-of-pipe solutions to encompass broader aspects of resource efficiency (Wilts et al., 2016). This need has spurred research into various MSW management strategies. For example, the separate collection of the organic fraction of municipal solid waste (OFMSW), the implementation of a deposit–refund system (DRS), and the enhancement of waste-to-energy (WTE) schemes, along with integrated approaches, have been studied in the context of the 2035 European Union (EU) targets. Such interventions were successfully modeled for target achievement in the Czech Republic (Kudela et al., 2020).

Despite MSW management systems (Sun et al., 2020) inherently being networks of waste generators, sorting and transfer facilities,

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Abbreviations

BP	Biogas Plant
CP	Composting Plant
DD	Dél-Dunántúl (South Transdanubia) region
DDNM	Directed Dynamic Multilayer Network
DMN	Dynamic Multilayer Network
DRS	Deposit–Refund System
ED	Észak-Dunántúl (North Transdanubia) region
EK	Észak-Kelet Magyarország (Northeastern Hungary) region
EoL	End-of-Life
EU	European Union
G	Waste Generation (Municipalities)
GHG	Greenhouse Gas
HCSO	Hungarian Central Statistical Office
I	Incinerator
IMRaD	Introduction, Methods, Results, and Discussion
JCLP	Journal of Cleaner Production
KK	Közép-Kelet Magyarország (Central-Eastern Hungary) region
L	Landfill
LCA	Life Cycle Assessment
MBT	Mechanical Biological Treatment
MRF	Materials Recovery Facility
MSW	Municipal Solid Waste
NEIS	National Environmental Information System
OFMSW	Organic Fraction of Municipal Solid Waste
RDF	Refuse-Derived Fuel
SF	Selective Waste Sorting Facility
SRF	Solid Recovered Fuel
T	Tiszántúli (Trans-Tisza) region
TF	Transshipment Facility
WFD	Waste Framework Directive
WTE	Waste-to-Energy

and treatment plants, few studies have extensively applied network analysis, design, and optimization techniques to address MSW challenges. Some researchers have explored specific aspects: (Li et al., 2024) investigated construction waste recycling within a cross-regional network of firms, while (Cerqueti et al., 2020) used a complex network approach to identify homogeneous municipal communities based on waste management practices. However, these studies did not comprehensively model the material flow of MSW throughout the entire supply chain, from waste generation to final treatment, based on an integrated network structure. Instead, they focused on cross-sectional analyses of specific network levels.

In contrast, Olapiriyakul et al. (2019) proposed a multi-objective supply chain network design optimization approach for locating sorting facilities, landfills, and incinerators, demonstrated in Thailand. This model defined an optimal network structure based on objectives combining total cost, land use, and public health impact. For existing systems facing future challenges, the model by Kůdela et al. (2019) is more applicable, examining the locations and capacities of 116 transshipment and transfer stations. With households as waste sources aggregated on settlements, transshipment facilities and end-of-life solutions as nodes of a multi-layer transportation network, the problem resembles the Sustainable Joint Economic Lot Size Problem (Katiraee et al., 2024), in which the total supply chain is evaluated using sustainable performance measures, such as greenhouse gas emissions or environmental footprint, and holistic optimization is employed.

The analysis and comparison of various MSW management scenarios are crucial for developing optimal strategies. Table 1 summarizes key research focusing on scenario analysis in waste management.

A review of the literature reveals that few studies utilize scenario-based analysis for MSW management strategies while also making future projections. While scenario analyses have been conducted at various geospatial levels (municipal, regional, supranational, or global), and some have focused on separated waste fractions or future predictions, none have jointly applied detailed fraction analysis, geospatial networks, and future predictions to estimate settlement-level flows and environmental impacts from transport, such as CO_2 emissions, or to optimize MSW management systems topologically.

More specifically, there is no study analyzing the MSW management system on national, regional and municipal levels in the same time. Out of the relevant studies, only four dealt with separated waste flow during the analysis, three provided future predictions regarding to the system status and finally, none of them considered the system as a transportation network. This indicates that major research gap as: there is no study that (1) conducts the analysis across all the regional levels, (2) considers separated waste flows, (3) applies transportation network for the modeling of the MSW management system and (4) provides future predictions.

Therefore, this paper proposes a novel MSW management scenario analysis method that employs a dynamic multilayer network (DMN) structure. This DMN tracks separated waste fraction flows, incorporates future predictions, and spans municipal, regional, and national levels through specific network logic (see the last row of Table 1). This approach facilitates estimations of the evolution of various waste types across different scenarios at the municipal level and assessments of the subsequent environmental impacts of transportation. In Hungary, approximately 3.5 million tonnes (t) of MSW are currently generated annually. Of this, 46% is landfilled, 17% incinerated, 9% composted, and 29% recycled in 2021. Further transition to a circular economy can be fostered through government policies, infrastructure and technology improvements, heightened awareness, enhanced stakeholder collaboration, and ongoing supply chain integration (Mhatre et al., 2021). Consequently, this research undertakes a network-based exploratory analysis of the entire Hungarian MSW management sector to determine the system-level impact of implemented and planned strategies, using the carbon footprint as the primary indicator to describe system operation and development effects.

Scenario analysis in MSW management is crucial for examining the potential implementation and effectiveness of EU environmental regulations (e.g., Waste Framework Directive and Circular Economy Action Plan). A DMN representation offers significant advantages over traditional methods for such analyses. It can capture the complex interactions among different waste streams, treatment facilities, and transportation routes over time, providing a comprehensive and realistic model. The multilayer structure allows for separate analyses of various waste fractions and treatment processes, while the dynamic methodology enables the assessment of system evolution in response to policy changes or technological advancements. Furthermore, this approach facilitates the identification of spatial imbalances, inefficiencies in waste transportation, and potential areas for optimization, all critical for developing effective MSW management strategies. By incorporating geospatial data and focusing on detailed environmental impact estimations (e.g., CO_2 emissions), the DMN approach offers valuable insights for improving policy decisions and evaluating progress toward EU MSW management targets. This method also enables the exploration of synergies and trade-offs between different strategies, supporting integrated solutions that address multiple objectives simultaneously.

The specific aims of this paper are as follows:

Table 1
List of research papers focused on waste management scenario analysis.

Reference	Method	Short description	Level			SWF	Network	Prediction	Scenarios
			C	R	M				
Eghbali et al. (2022)	MOO	A sustainable supply chain network design for municipal solid waste management.		✓	✓	✓			3
Gómez-Sanabria et al. (2022)	Simulation (RAINS)	Analysis of reductions in global greenhouse gas and air pollutants from circular waste management systems.		✓				✓	2
de Medeiros Engelmann et al. (2022)	WARM	Construction of scenarios contributing to the implementation of modern and efficient solutions for MSW management.		✓		✓			114
Miao (2021)	LCA	A case study regarding the mitigation of greenhouse gas emissions from a municipal solid waste management system.			✓	✓			4
Kayakutlu et al. (2017)	Bayesian networks	Application of Bayesian networks to evaluate different investment scenarios in a municipality in Turkey.			✓				7
Liu et al. (2017)	Simulation (EaseTech)	Carbon and energy flow analyses and scenario analyses of municipal solid waste management in China.	✓			✓			5
Van Fan et al. (2022)	ANN	Machine learning is used to identify hidden patterns in plastic waste generation and waste amount forecasting based on different EU scenarios through 2030.	✓					✓	5
Wang et al. (2022)	LSTM NN	Analysis of the municipal solid waste generation process in Shanghai.		✓				✓	3
Current paper			✓	✓	✓	✓	✓	✓	4

C = country, R = region, M = municipality, SWF = separated waste fraction.

A_1 **To develop a methodology for representing MSW management systems as a directed dynamic multilayer network (DMN).** Achieving this aim addresses a critical gap in municipal solid waste management scenario modeling, as outlined in Table 1, where state-of-the-art methods typically do not integrate detailed transition networks with future predictions.

A_2 **To analyze the feasibility and efficiency of various MSW management scenarios proposed by the Hungarian Government.** The developed DMN-based model is applied to Hungarian waste generation and treatment data, constructing the entire municipal solid waste treatment network from multiple datasets. After predicting future municipal solid waste generation and transitions, the defined MSW management scenarios are compared and analyzed for their efficiency and feasibility.

A_3 **To reveal the inherent characteristics of the Hungarian MSW transition network.** Compared to existing methods, the proposed DMN-based model provides more detailed and valuable insights into the topological and operational aspects of the Hungarian MSW management system.

The contributions of this paper, associated with each research aim, are as follows:

C_1 **We provide a novel DMN-based MSW management system model and scenario analysis method that supports a more comprehensive understanding of the entire municipal solid waste management cycle.** This model is adaptable for application in other countries, enabling researchers to conduct in-depth analyses of interconnections among actors within the MSW management system and offering new avenues for network sensitivity analysis or topological optimization.

C_2 **We explore the efficiency and effectiveness of each proposed strategy in achieving the European Union's 2035 targets within various scenarios.** Assessing efficiency and feasibility for each planned scenario provides crucial early warning information for decision-makers, allowing for necessary interventions or controls.

C_3 **Revealing the weak points of the MSW treatment network empowers decision-makers to rationalize the management system and decrease country-level CO_2 emissions.** By exploring network vulnerabilities, transition strategies and capacity planning can be optimized to reduce the total path length of the network, thereby avoiding unnecessary transportation of waste.

The structure of the paper is organized as follows: Section 2 details the proposed methodology, Section 3 presents the analytical results, Section 4 discusses these findings, and finally, Section 5 summarizes the conclusions and implications.

2. Methods

In Sections 2, 2.1 introduces the MSW management system in the study area, Section 2.2 discusses the dynamic multilayer network construction with the data preprocessing steps and Section 2.3 presents the policy scenarios for MSW decarbonization.

The framework of the proposed dynamic multilayer network (DMN)-based scenario analysis method is presented in Fig. 1.

As Fig. 1 shows, the framework consists of three main steps: (1) data collection and preprocessing, (2) dynamic multilayer network construction, and (3) modeling and analysis of possible MSW policy measure scenarios. Detailed descriptions of these steps are provided below.

2.1. Overview of the Hungarian Municipal Solid Waste management system

In Hungary, an integrated MSW management system (Seadon, 2006) has been developed, which coordinates waste generation from different regions with facility infrastructure planning based on waste volume

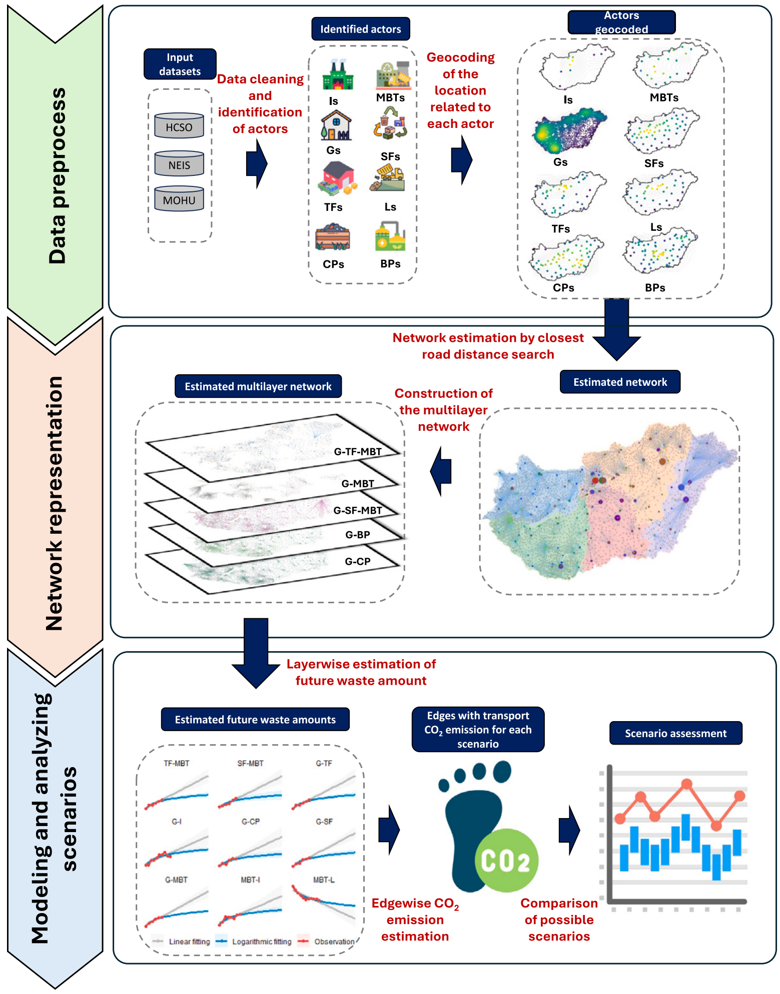


Fig. 1. The framework of the proposed Dynamic Multilayer Network (DMN) methodology, illustrating the three main steps: (1) Data Collection and Preprocessing, (2) Dynamic Multilayer Network Construction for the municipal solid waste transition system, and (3) Modeling and Analysis of potential MSW transition scenarios.

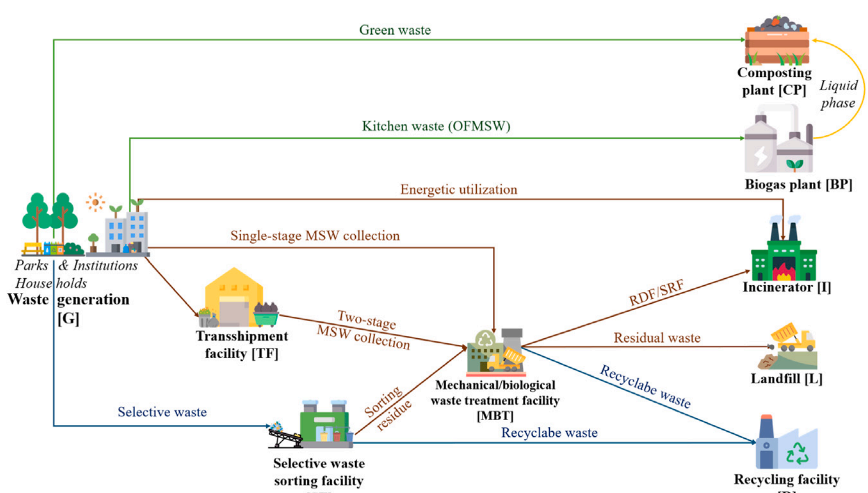


Fig. 2. Schematic representation of a typical Municipal Solid Waste (MSW) management system, illustrating key stages and facilities: Waste Generation (G), Transshipment Facilities (TF), Mechanical Biological Treatment (MBT) plants, Selective Waste Sorting Facilities (SF), Composting Plants (CP), Biogas Plants (BP), Incinerators (I), and Landfills (L).

and logistics, following the principle of economy of scale. Fig. 2 illustrates the general structure of an MSW management system, indicating different waste fractions and facility types.

MSW can be broadly categorized by origin and further grouped by waste fraction. This research specifically explores MSW disposal and utilization options within the network topology of the Hungarian MSW management system. Waste collection can be single-stage, where collected waste is transported directly to a treatment center, or two-stage, involving initial transport to transshipment facilities (TFs) before onward transport by larger vehicles to treatment plants (Li et al., 2023). Practical guidelines suggest constructing a TF when annual waste volume exceeds 12–15 thousand tonnes (t) and transport distances for waste treatment are over 40–100 km (Inghels et al., 2016). Selective waste collection involves the separate collection of materials such as paper/cardboard, light packaging (plastic, ferrous, and non-ferrous metals), and glass (Ferreira et al., 2017). These are processed into useful materials at selective waste sorting facilities (SFs) using technologies like air classifiers, sink-float sorting, magnetic sorting, and sensor-based sorting (Lange, 2021).

Mechanical biological treatment (MBT) processes combine shredding, size/shape sorting, specific gravity sorting, metal separation, material sorting, post-shredding, biological stabilization, and preparation for transport (Tyagi et al., 2021). Depending on composition, treated waste fractions can be incinerated (Saner et al., 2011) as solid recovered fuel (SRF) (Viczek et al., 2020) or refuse-derived fuel (RDF) (Sarquah et al., 2022), landfilled (D'Inverno et al., 2024; Paul and Ghosh, 2022), or recycled (Bruno et al., 2021). The organic fraction of MSW (OFMSW) includes kitchen waste and green waste. The Waste Framework Directive (WFD) 2008/98/EC (Gharfalkar et al., 2015) mandates EU Member States to collect biowaste separately to reduce landfilling. Consequently, separate collection of kitchen waste (Kuligowski et al., 2023) has begun implementation in Hungary (Tóth et al., 2023) as a pilot project, however, we have only partial and early experience so far.

2.2. Dynamic multilayer network construction

A directed dynamic multilayer network (DMN) $\mathcal{M}_t = (\mathcal{G}_t, \mathcal{C}_t)$ is constructed to represent the Hungarian MSW management system (Boccaletti et al., 2014). This network is defined by a family of graphs $\mathcal{G}_t = \{G_t^\alpha = (V_t^\alpha, E_t^\alpha), \alpha \in \{1, \dots, M\}, t \in T\}$, where G_t^α represents a specific layer (based on edge type) at time t. V_t^α is the set of nodes (vertices) in layer α at time t, E_t^α is the set of directed edges (arcs) in layer α at time t, and T is the set of years. Interlayer edges are not explicitly defined in this formulation as layers are separated by edge types, meaning $\mathcal{C}_t = \emptyset, \forall t \in T$. All locations (nodes) are geolocated, and directed edges establish flow paths where head and tail nodes have distinct roles.

2.2.1. Node sets

The nodes in our DMN represent the various actors within the MSW management system, corresponding to the stages presented in Fig. 2. These node types, along with their roles, are detailed in Table 6 in Appendix A.

- **Generators (G):** These represent the municipalities (settlements) where MSW is generated. They are the initial source nodes in the network.
- **Transshipment Facilities (TF):** Intermediate nodes where waste is temporarily aggregated before being transferred to larger treatment facilities, often for optimizing transport logistics over longer distances.
- **Mechanical Biological Treatment (MBT) Facilities:** Nodes representing facilities that process mixed waste through mechanical sorting and biological stabilization.
- **Selective Waste Sorting Facilities (SF):** Nodes where separately collected waste fractions (e.g., paper, plastic, glass) are sorted and prepared for recycling.
- **Composting Plants (CP):** End-of-life (EoL) nodes where OFMSW is aerobically decomposed to produce compost.
- **Biogas Plants (BP):** EoL nodes where OFMSW undergoes anaerobic digestion to produce biogas.
- **Incinerators (I):** EoL nodes where waste is combusted to generate energy (Waste-to-Energy).
- **Landfills (L):** EoL nodes for the final disposal of residual waste that cannot be further treated or recycled.

2.2.2. Layers and directed edges

The DMN is structured into distinct layers based on the type of material flow (edge type) between different facility types. This layer separation, as shown in Table 2, allows for a granular analysis of municipal solid waste movement. Each layer consists of directed edges, where the direction indicates the flow of waste from a source node (head node) to a destination node (tail node). These edges represent annual MSW flows, typically measured in tonnes per year. Associated with each edge are transport distances, which are crucial for calculating transport-related GHG emissions. Cross-layer mapping is implicitly handled by the definition of layers based on edge types; a single physical facility (node) can participate in multiple layers as a head or tail node, reflecting its different roles in the MSW flow.

2.2.3. Temporal evolution

The DMN is dynamic, allowing for the analysis of system evolution over time. The time steps cover a baseline year (2021 in this study) and forecast years leading up to 2035. Over this period, attributes associated with nodes (e.g., facility capacities) and edges (e.g., waste diversion rates, flow volumes) are updated to reflect changes due to policy measures, technological advancements, or predicted MSW generation trends. Scenario parameters are explicitly designed to instantiate these changes, detailing how specific policies or developments (e.g., new facilities, altered collection schemes) impact the network's structure and flow attributes at each time step.

2.2.4. Edge weights and emissions calculation

Each edge in the network is weighted by the amount of municipal solid waste transported in tonnes for a given year. The environmental impact, specifically GHG emissions, is computed for both transport and treatment processes.

- **Transport Emissions:** Transport GHG emissions are calculated for each edge based on the physical distance between the connected nodes and a mode-specific emission factor. For road transport, the "EU-28: Transport, truck (20 t total cap., 17.3 t payload)" factor is used, corresponding to 0.0839 kg $CO_{2eq.}$ per 1000 kg km (Sphera, 2022). The model accounts for the impact of returning empty.
- **Technological Emissions:** Emissions associated with municipal solid waste treatment processes are attached to the nodes (facilities) via LCA factors, which are applied to the incoming waste volumes. These factors, sourced from the Sphera database (Sphera, 2022) (software version 10.6.1.35), are:
  - **Landfill (L):** 0.838 kg $CO_{2eq.}/kg_{\text{waste}}$ (EU-28: Municipal waste landfill (EN15804 C4) Sphera)
  - **Incineration (I):** 1.26 kg $CO_{2eq.}/kg_{\text{waste}}$ (EU-28: Commercial waste in municipal waste incineration plant Sphera)
  - **Composting (CP):** 0.508 kg $CO_{2eq.}/kg_{\text{waste}}$ (AT: Open windrow composting (finished compost) BOKU/Sphera)
  - **Biogas Production (BP):** −0.0662 kg $CO_{2eq.}/kg_{\text{waste}}$ (EU-28: Biomethane from municipal organic waste Sphera), indicating a net GHG emission reduction.

The cumulative CO_2 emissions associated with edges for different scenarios are summarized in Table 7.

Table 2
Set of layers based on edge types with edge counts in 2021. The layers define the specific types of waste flow between different actors in the municipal solid waste management system.

No	Layer name/Edge type	Head node	Tail node	Count
1	G-MBT	(G) Waste generation	(MBT) Mechanical/biological waste treatment facility	1195
2	G-TF	(G) Waste generation	(TF) Transshipment facility	1958
3	TF-MBT	(TF) Transshipment facility	(MBT) Mechanical/biological waste treatment facility	45
4	G-SF	(G) Waste generation	(SF) Selective waste sorting facility	3154
5	G-CP	(G) Waste generation	(CP) Composting plant	3154
6	MBT-L	(MBT) Mechanical/biological waste treatment facility	(L) Landfill	23
7	MBT-I	(MBT) Mechanical/biological waste treatment facility	(I) Incinerator	23
8	SF-MBT	(SF) Selective waste sorting facility	(MBT) Mechanical/biological waste treatment facility	56
9	G-I	(G) Waste generation	(I) Incinerator	20
10	G-BP	(G) Waste generation	(BP) Biogas plant	3154

2.2.5. Data sources and preprocessing

The construction of the DMN relies on several primary data sources and a series of preprocessing steps:

1. **Data Collection:**
   - **Waste Types, Facility Locations, and Generated Waste Amounts:** Provided by the Hungarian Central Statistical Office (HCSO).
   - **Additional Actor Information:** Obtained from the National Environmental Information System (NEIS) and data tables provided by MOHU Ltd., covering details for Mechanical Biological Treatment (MBT), Generators (G), Selective Waste Sorting Facilities (SF), Transshipment Facilities (TF), Landfills (L), Composting Plants (CP), and Biogas Plants (BP).

   The detailed structure of the dataset used, including network, weights, prediction, and scenario columns, is presented in Table 5 in Appendix A.
2. **Data Cleaning and Actor Identification:** Initial datasets were cleaned to identify and consolidate information about the main actors (G, TF, MBT, SF, CP, BP, L, I), including their names, addresses, and organizational affiliations.
3. **Geocoding:** The identified actors were geocoded using a Python script developed by Csizmadia and Katona (2022), converting physical addresses into geographical coordinates (latitude and longitude).
4. **Network Estimation and Distance Calculation:** The waste management network edges were established based on the shortest road distance between actors. For each specific source (e.g., a municipality), road distances were calculated to all potential destination nodes across the network, and the endpoint node with the shortest road distance was selected. The *OSMnx* Python package (Boeing, 2024) was used for these road distance calculations.
5. **Multilayer Network Structuring:** The established network was restructured into layers according to the type of edge, as defined in Table 2. This step categorized each municipal solid waste flow connection into its respective layer based on the types of nodes it connects.
6. **Layer-wise Data Imputation:** For municipalities with missing MSW amount data for specific years, data imputation was performed. Missing data points were estimated via interpolation based on available yearly data points.
7. **Estimation of Future MSW Amounts:** The existing time series of waste amounts per municipality (up to 2021) was extrapolated through 2035. A logarithmic function, consistent with findings by Pavlas et al. (2020) and yielding better R^2 values compared to linear models, was applied for this extrapolation. The equation used is $y_i = \alpha + \beta \ln(x)$, where y_i is the predicted aggregated municipal solid waste amount for the ith edge type, x is the actual year, and α and β are optimized model parameters. Fig. 4 illustrates the results of this curve fitting for each edge type.

To go from raw data to a time-indexed DMN instance for each scenario, the following steps are performed: First, geospatial data for all MSW generators and facilities are collected and geocoded. Next, shortest road distances are calculated between all possible node pairs. Then, historical municipal solid waste flow data are mapped onto these potential network edges, defining the baseline layer structures and edge weights. Missing historical data are imputed, and future waste generation is forecasted using logarithmic regression. Finally, for each policy scenario and year, the forecasted waste flows are adjusted according to specific policy interventions (e.g., diversion rates, new capacities) to create a distinct time-indexed DMN instance, allowing for the calculation of transport and treatment GHG emissions.

The Hungarian MSW management system is coordinated across seven waste management regions, which include the actors listed in Table 2. The entire network structure with a regional breakdown is presented in Fig. 3.

The network structure in Fig. 3 is visualized using the following concepts:

- The **size** of waste generation (G), transshipment facility (TF), mechanical biological treatment (MBT) facility, and selective waste sorting facility (SF) nodes is determined by the quantity of waste transported. For final destination nodes (composting plant (CP), biogas plant (BP), landfill (L), and incinerator (I)), the size is proportional to the total incoming waste quantity.
- The **node colors** are consistent with the definitions provided in Table 6.
- The **lines** between nodes represent the directed flow of MSW within the network.

Fig. 3 illustrates the uneven distribution of MSW management infrastructure across Hungary. Western regions show a more uniform distribution, while eastern areas rely on a limited number of intermediate facilities, such as TFs and MBTs. This disparity reflects the country's municipal structure, with the central Budapest region serving as a major hub.

The MSW management regions, indicated by different background colors in Fig. 3, have the following statistical characteristics:

- **Észak-Dunántúl (ED) region (Blue):** Includes 764 settlements with a total population of 1,627,767. Total area: 16,674 km^2 (average population density: 97.62 km^{-2}). Facilities: 12 TFs, 5 MBT facilities, 14 SFs, 6 CPs, 9 Landfills, and 1 Incinerator.
- **Dél-Dunántúl (DD) region (Green):** Includes 948 settlements with a total population of 1,347,707. Total area: 19,763 km^2 (average population density: 68.19 km^{-2}). Facilities: 10 TFs, 6 MBT facilities, 13 SFs, 14 CPs, 6 Landfills, and 4 Incinerators.
- **Budapest térség (B) region (Brown):** Includes 71 settlements with a total population of 2,346,519. Total area: 2271 km^2 (average population density: 1033.25 km^{-2}). Facilities: 5 TFs, 1 MBT facility, 3 SFs, 3 CPs, 2 Landfills, and 3 Incinerators.

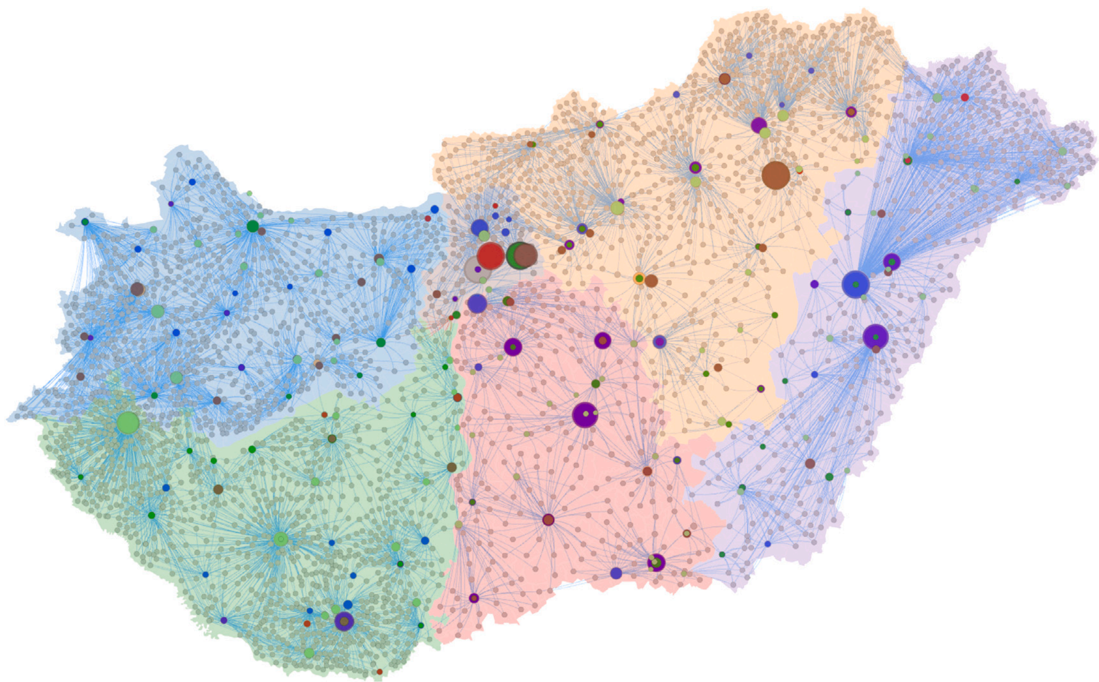


Fig. 3. Network representation of the Municipal Solid Waste (MSW) management system in Hungary according to regional coordination (in Map of Hungary). Node sizes are proportional to the transported waste quantity. Node colors correspond to facility types as defined in Table 6. Background colors delineate the following regions: Észak-Dunántúl (ED, blue); Dél-Dunántúl (DD, green); Budapest térség (B, brown); Közép-Kelet Magyarország (KK, red); Észak-Kelet Magyarország (EK, orange); and Tiszántúli (T, purple).

- **Közép-Kelet Magyarország (KK) region (Red):** Includes 243 settlements with a total population of 1,399,442. Total area: 15,484 km^2 (average population density: 90.38 km^{-2}). Facilities: 5 TFs, 3 MBT facilities, 7 SFs, 9 CPs, and 6 Landfills.
- **Észak-Kelet Magyarország (EK) region (Orange):** Includes 730 settlements with a total population of 1,733,539. Total area: 21,604 km^2 (average population density: 80.24 km^{-2}). Facilities: 8 TFs, 7 MBT facilities, 14 SFs, 15 CPs, 10 Landfills, and 1 Incinerator.
- **Tiszántúli (T) region (Purple):** Includes 398 settlements with a total population of 1,422,210. Total area: 17,214 km^2 (average population density: 82.62 km^{-2}). Facilities: 5 TFs, 1 MBT facility, 5 SFs, 13 CPs, 4 Landfills, and 2 Incinerators.

2.3. Policy scenarios for MSW decarbonization

To describe the transition of the MSW management sector, we analyze the impact of changes in waste streams on CO_2 emissions to determine optimal strategies. The MSW management sector faces numerous legal challenges; for instance, the amount of MSW prepared for reuse and reprocessing must increase to a minimum of 65% by 2035 (European Parliament, 2018b). Biowaste must be either separated and recycled at the point of origin or collected separately and not mixed with other waste types (European Parliament, 2018b). By 2035, the amount of MSW landfilled should be reduced to 10% or less of the total generated MSW (European Parliament, 2018a), and by 2030, at least 70% of all packaging waste must be recycled (European Parliament, 2018c). Furthermore, the separate collection of plastic products must achieve a 90% rate for single-use plastic products by 2029 (European Parliament, 2019). These legal requirements entail varying deadlines and implementation intensities. Thus, we consistently examine the impacts of sectoral changes projected for the year 2035. Given that legal regulations define overarching targets, the following MSW policy scenarios are formulated:

1. **Baseline Scenario:** The baseline scenario serves as a reference for comparative evaluation of intervention impacts, modeled using a data-driven nonlinear regression model. This scenario reflects the projected state of the MSW management network in 2035 without any structural changes or new diversion policies. It assumes no changes in waste flow distribution between edge types beyond historical trends.
A logarithmic function ($y_i = \alpha + \beta \ln(x)$) was applied for extrapolation, drawing inspiration from Pavlas et al. (2020)'s work on realistic future targets. This approach was chosen because linear models exhibited unrealistic increases by 2035 due to sensitivity to recent data patterns. The logarithmic models, conversely, yielded better R^2 values and aligned with observed trends. Fig. 4 displays the curve fitting results for each edge type, with the y-axis normalized to the 2021 waste amount for better interpretability. It is important to highlight, that use of other models were also considered such as ARIMA or LSTM. Since LSTM is a deep learning based architecture, it requires huge amount of data to learn the complex patterns behind the data, and this method was developed to predict long term periods (Wang et al., 2023; Krichen and Mihoub, 2025). Due to the high complexity (black-box nature) and the long-term focus, we decided to reject LSTM during the forecast. ARIMA was also tested in forecasting the overall waste amount until 2035, however, compared to the logarithmic model, ARIMA strongly overestimates the trend since it does not consider the decreasing effects from the EU directives and is too sensitive to the recent data points. This two reasons results an unrealistic increasing trend forecasted by ARIMA as an annal average ∼2.5% growth rate compared to the ∼0.52% estimated by the logarithmic model. The two predicted scenarios are shown by Fig. 12 in Appendix B.
2. **Organic Fraction of Municipal Solid Waste (OFMSW) Separation Scenario:** This scenario models the separate collection of the organic fraction of municipal mixed waste (estimated at 20 m/m% of total mixed waste) and its utilization at biogas

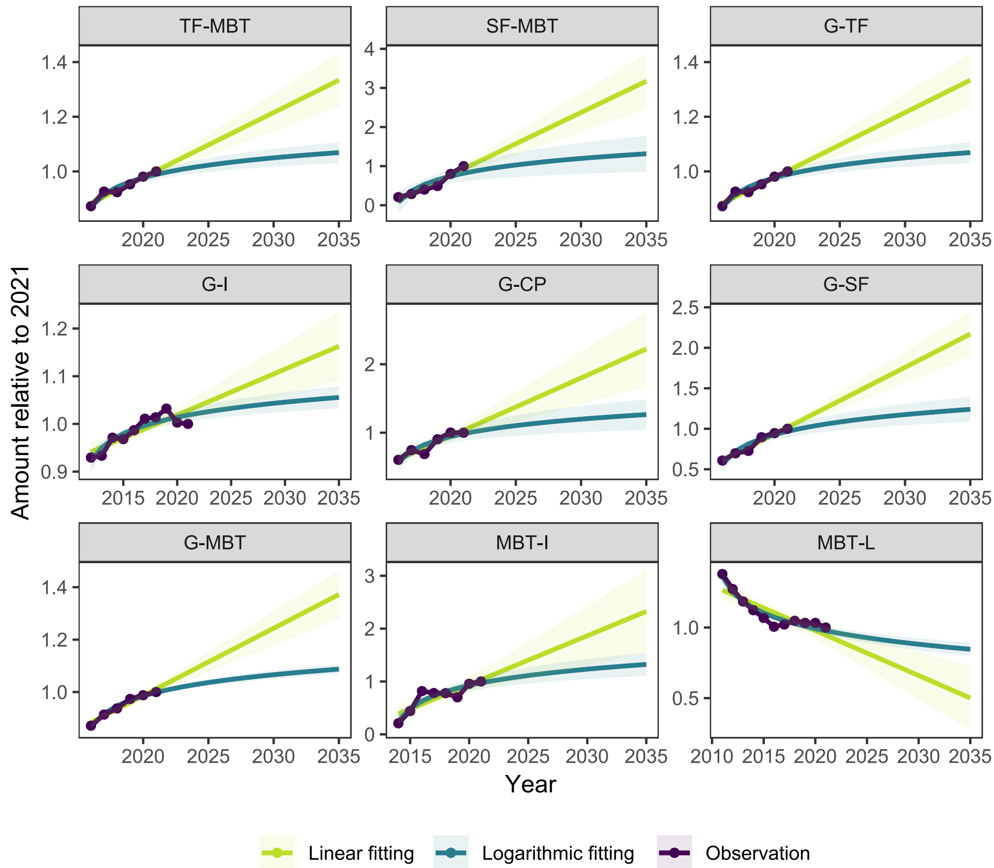


Fig. 4. Estimation of Municipal Solid Waste (MSW) fractions for various edge types. The *y*-axis shows the relative waste amount compared to the 2021 baseline, illustrating the extrapolated trends to 2035 for each waste flow category.

plants. This intervention directly reduces the amount of landfilled waste and increases resource recovery. In 2021, mixed MSW was 2,717,015 tons (Hungarian Central Statistical Office, 2024), which is expected to be 2,173,612 tons by 2035. Based on the 20 m/m% experience of laboratory waste analyses, the organic fraction can be estimated at 543,403 tons.

3. **Deposit–Refund System (DRS) Scenario:** This scenario describes the impacts of intensively promoting the reuse and recycling of one-way packaging materials. A total of 158,000 tonnes of useful material is diverted from the mixed and selectively collected MSW fractions (Szűcs et al., 2024). This diversion occurs at both initial collection points and at selective and end-of-life treatment facilities. Currently, metal, plastic, and glass beverage packages are sold with a uniform deposit fee of 50 HUF (~0.14 €), redeemable at 2657 points nationwide.
4. **Waste-to-Energy (WTE) Scenario:** This scenario explores the reduction of landfilled waste by increasing energy utilization. In 2021, disposal by incineration amounted to 388,579 tonnes, which is expected to increase to 410,140 tonnes by 2035. It specifically analyzes the impacts of a hypothetical new incineration plant with an annual capacity of 300,000 tonnes of MSW. This strategy aims to shift waste away from landfills towards energy recovery. The location of the new incineration plant was determined taking into account the national amounts of combustible MSW generation patterns.
5. **Waste Transition Scenario:** This comprehensive scenario represents a joint implementation of the OFMSW separation, DRS, and WTE strategies. It involves a set of integrated measures covering the entire MSW management sector, aiming for a holistic transformation towards decarbonization and resource efficiency.

3. Results

Section 3 is structured as follows: Section 3.1 presents the results for transport path lengths. This followed by the obtained results on carbon footprints (Section 3.2) and regional characteristics (Section 3.3). Finally, Sections 3.4 and 3.6 cover the scenario analysis and end-of-life hotspot-related results, respectively.

3.1. Transport path lengths and emissions for different edge types

The efficiency challenges within the MSW management sector are intrinsically linked to its network topology, specifically the availability and relative distance of disposal and utilization facilities from waste generation sites, as depicted in Fig. 5.

Fig. 5 illustrates the geographical distribution of cumulative transport distances. Nodes represent locations, and edges signify transport paths. While edges are shown as straight lines for visualization, actual road distances were used for calculations. The average cumulative path length between a source location and the nearest utilization facility is 116.0 km. The shortest routes occur when processing plants are located in close proximity to settlements. Conversely, the longest routes are observed in the Tiszántúli (Trans-Tisza) region (T). The top five settlements with the longest routes — Tiszagyenda (307.0 km), Örményes (299.3 km), Kunhegyes (297.6 km), Túrkeve (293.5 km), and Tiszaszentimre (293.5 km) — are all situated in this region. This extended transport is primarily due to the scarcity of processing plants, such as landfills and incinerators, in the Tiszántúli region, necessitating waste transport to other regions.

Fig. 5 colors settlements according to their cumulative path lengths, highlighting the total distance individual waste fractions travel

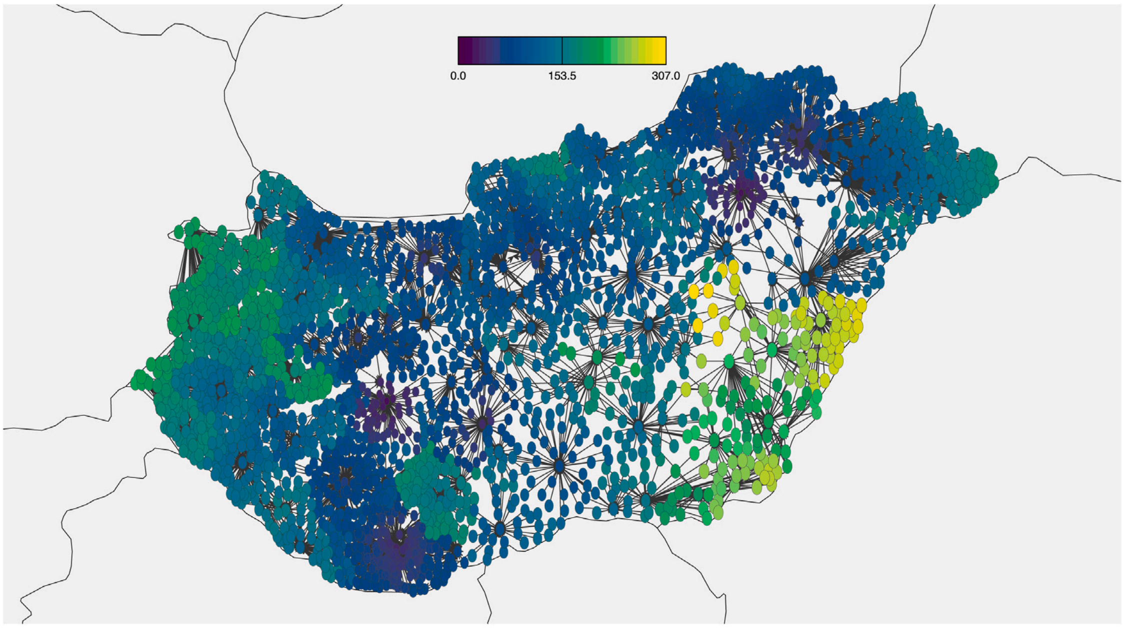


Fig. 5. Cumulative transport distance of Municipal Solid Waste (MSW) fractions across the entire waste management process (in km), mapped to source locations (settlements) based on 2021 data. Node colors indicate the cumulative path length, with darker shades representing longer distances. Although edges are shown as straight lines for clarity, calculations utilized actual road distances.

throughout the entire MSW management process. The maximum cumulative distance for a waste fraction is 307 km. However, system efficiency must also consider the volume of waste transported, making a CO_2-based representation more informative. Fig. 6 presents CO_2 emissions (in tonnes) for each trip, categorized by edge type. The logarithmic size and color of the source nodes (locations) are proportional to their associated CO_2 emissions. Tail nodes of directed edges correspond to processing locations, with CO_2 emissions attributed to each source.

We also examined how capacity constraints would affect the transportation network if the closest facility became unavailable to process MSW. Therefore a simulated version of the network is generated assuming that MSW is transported always to the second closest facility from to the given source actor. This scenario results in a ~1.7-fold increase in both the average path length across the network and the total network path length. However this study does not deal with capacity planning optimization, the results suggests that capacity issues should be treated with regional backup puffer capacities instead of network restructuring as it is sensitive to capacity constrains.

Fig. 6 reveals varying network densities across different layers. The densest networks are observed in the waste generation to selective waste sorting facility (G-SF) layer (Fig. 6(d)) and the waste generation to composting plant (G-CP) layer (Fig. 6(e)), suggesting these facilities are often located near settlements. Conversely, connections between waste generation and incinerators (G-I) are the least dense (Fig. 6(i)). Layers representing waste generation to transshipment facility (G-TF) (Fig. 6(a)) and waste generation to mechanical biological treatment facility (G-MBT) (Fig. 6(b)) show moderate density, while others are sparse. Long edges in these diagrams, particularly those with high CO_2 emissions, highlight opportunities for significant reductions through network optimization. For example, the long transport path from the Tiszántúli (T) region to the Észak-Kelet Magyarország (EK) region in the MBT-I layer (Fig. 6(g)) underscores the need for incineration capacity in the Tiszántúli region to reduce CO_2 emissions.

3.2. Carbon footprint of MSW transport

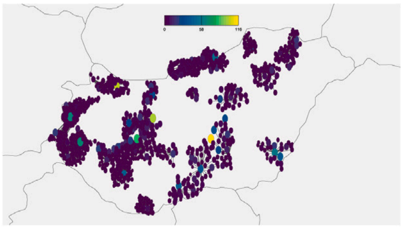
In 2021, MSW transportation collectively contributed 20,812 tonnes of CO_2 emissions. Approximately 77% of these emissions were associated with waste collection within settlements and subsequent transport to mechanical biological treatment (MBT) facilities. Given that MBT facilities have historically been situated near landfills, the MBT-L edge (from MBT to landfill) accounts for only 0.12% of the total transport CO_2 footprint (see Table 7). However, new end-of-life (EoL) scenarios, which aim to divert waste from landfills in alignment with long-term MSW management goals, are likely to increase transport distances. This implies significant potential for reorganizing MBT and other facilities to minimize the carbon footprint of transportation. Optimizing the topology of the MSW management network could considerably reduce transport-related CO_2 emissions. Shifting from a landfill-oriented system towards utilization may necessitate establishing new technological facilities in the long term, whose optimal placement would contribute to sustainable system operation. This research lays the foundational groundwork for such methodological developments through detailed modeling and network-based CO_2 exploration analyses of the MSW system.

3.3. Regional characterization of the Hungarian MSW system

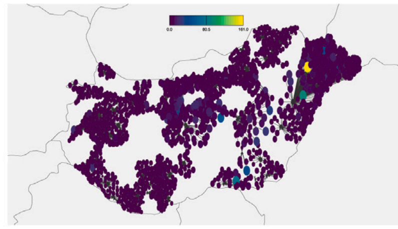
Fig. 7 illustrates the differences in MSW management practices across Hungarian regions, comparing the currently utilized transportation scheme with an idealized network structure based solely on distance-based assignments.

As shown in the G-MBT subplot of Fig. 7, approximately 80% of settlements in the Tiszántúli (T) region could achieve shorter transportation paths by connecting to MBT facilities in the neighboring Észak-Kelet Magyarország (EK) region. This highlights the underrepresentation of MBT facilities within the Tiszántúli (T) region. A similar pattern is observed in the SF-MBT layer, where around 50% of selective waste sorting facilities (SFs) in a given region have longer transport distances to within-region MBTs compared to those in other regions, suggesting that sorted waste could be more efficiently transported to MBTs in the Észak-Kelet Magyarország (EK) region.

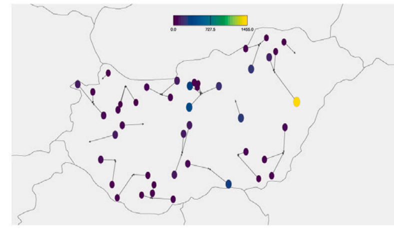
The MBT-L and MBT-I subplots in Fig. 7 reflect the characteristics of the existing MSW management system, which was historically oriented towards landfilling. In the MBT-L layer, the absence of prominent ribbons indicates good landfill coverage across all regions, where within-region MBT-L paths are generally shorter than cross-region alternatives. Conversely, the MBT-I subplot clearly shows that MSW from



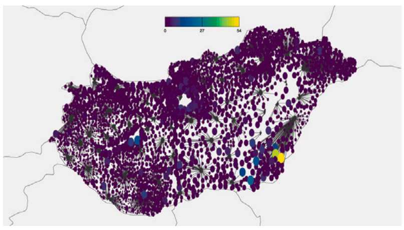
(a) Waste Generation (G) to Transshipment Facility (TF)



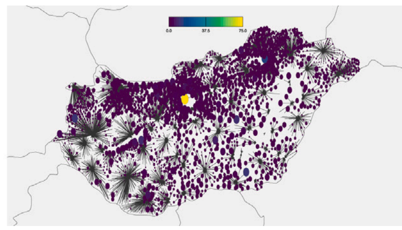
(b) Waste Generation (G) to Mechanical Biological Treatment (MBT) facility



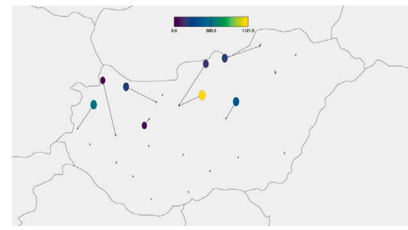
(c) Transshipment Facility (TF) to Mechanical Biological Treatment (MBT) facility



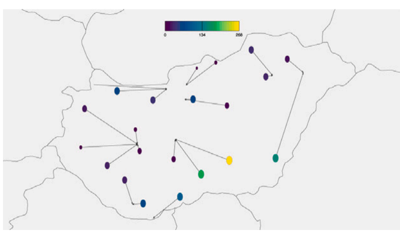
(d) Waste Generation (G) to Selective Waste Sorting Facility (SF)



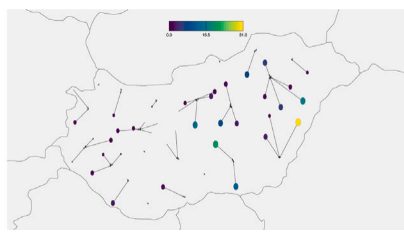
(e) Waste Generation (G) to Composting Plant (CP)



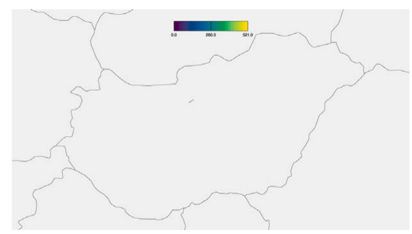
(f) Mechanical Biological Treatment (MBT) facility to Landfill (L)



(g) Mechanical Biological Treatment (MBT) facility to Incinerator (I)



(h) Selective Waste Sorting Facility (SF) to Mechanical Biological Treatment (MBT) facility



(i) Waste Generation (G) to Incinerator (I)

Fig. 6. CO_2 emissions (in tonnes) from Municipal Solid Waste (MSW) transportation linked to source locations for the year 2021. The logarithmic size and color of the source nodes represent the magnitude of CO_2 emissions originating from that location for the specified edge type; (a) Waste Generation (G) to Transshipment Facility (TF); (b) Waste Generation (G) to Mechanical Biological Treatment (MBT) facility; (c) Transshipment Facility (TF) to Mechanical Biological Treatment (MBT) facility; (d) Waste Generation (G) to Selective Waste Sorting Facility (SF); (e) Waste Generation (G) to Composting Plant (CP); (f) Mechanical Biological Treatment (MBT) facility to Landfill (L); (g) Mechanical Biological Treatment (MBT) facility to Incinerator (I); (h) Selective Waste Sorting Facility (SF) to Mechanical Biological Treatment (MBT) facility; (i) Waste Generation (G) to Incinerator (I).

across the country must be transported to neighboring regions for incineration due to the limited number of incinerators nationwide. This phenomenon leads to substantial cross-regional waste flows for incineration.

When comparing the aggregated edge distance under two scenarios — (1) all actors transport to an adequate point in the same waste management region (unless no in-region opportunity exists), and (2) all actors transport to the nearest point regardless of region — significant differences emerge. The aggregated edge distance is 411,233 km in the first case, and 389,865 km in the case without the same-region restriction, demonstrating a 21,367 km (approximately 6%) decrease in total transport distance across the entire network by optimizing purely on proximity.

3.4. Scenario analysis of MSW transported volume

Fig. 8 illustrates the distribution of the total quantity of different municipal solid waste fractions transported via the network edges, based on the system structure presented in Fig. 2.

It is important to note that in Fig. 8, the sum of waste amounts transported via edges exceeds the amount of MSW generated because, in a two-stage collection system, waste is transported multiple times (e.g., from generator to transshipment, then transshipment to MBT). Consequently, lower values in the modeled scenarios for 2035, compared to the baseline, indicate a simplification of the network structure and reduced overall transport activity, rather than a direct reduction in generated waste quantity.

In 2021, the total transported volume (sum of all edge flows) was 6.77 million tonnes (Mt). This is projected to increase to 7.12 Mt in the 2035 baseline scenario. In 2021, the largest material flow occurred on MBT-L edges (1.6 Mt), followed by G-TF and TF-MBT (cumulative 1.39 Mt). Other significant flows included G-SF (0.67 Mt), G-MBT (0.76 Mt), and G-I (0.39 Mt). Smaller flows were observed on MBT-I (0.2 Mt) and SF-MBT (0.05 Mt), with no flow on G-BP edges.

For the 2035 baseline, the largest transported quantities are projected on G-TF and TF-MBT edges (cumulative 1.49 Mt), while MBT-L flows decrease to 1.36 Mt. Increases are expected for G-SF (to 0.83 Mt), G-MBT (to 0.82 Mt), G-I (to 0.41 Mt), G-CP (to 0.4 Mt), and MBT-I (to 0.27 Mt). SF-MBT flows show little change (0.06 Mt), and G-BP remains negligible.

Critically, in the comprehensive Waste Transition scenario, the total transported MSW quantity is projected to be 5.90 Mt, as it is

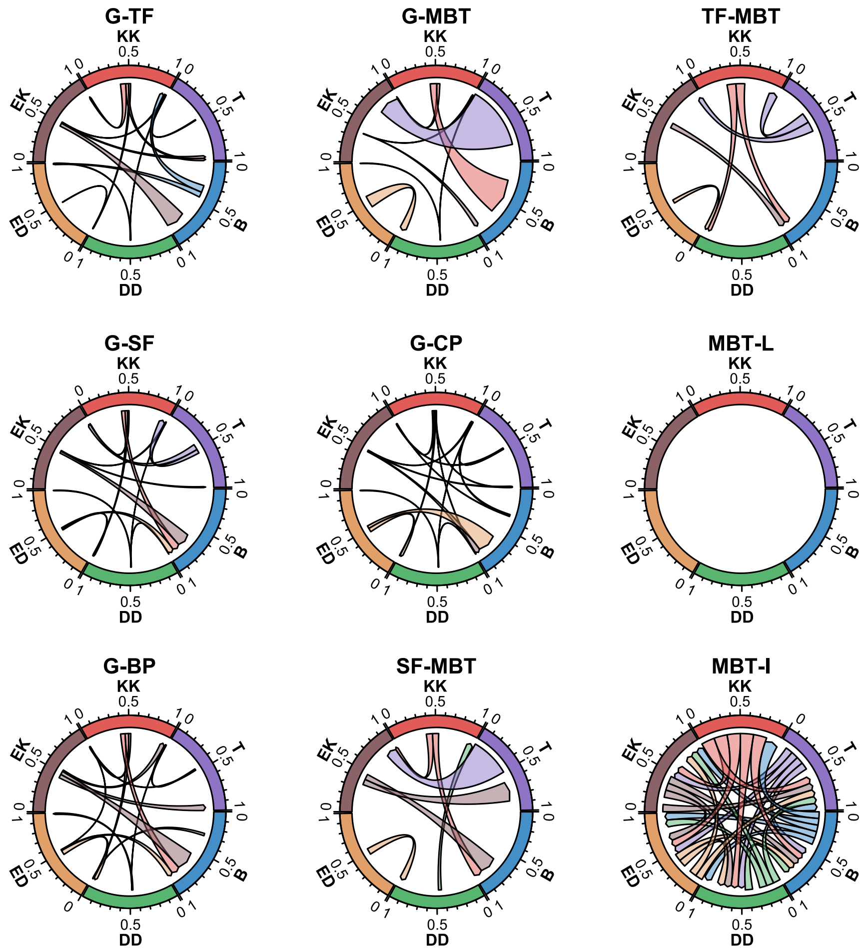
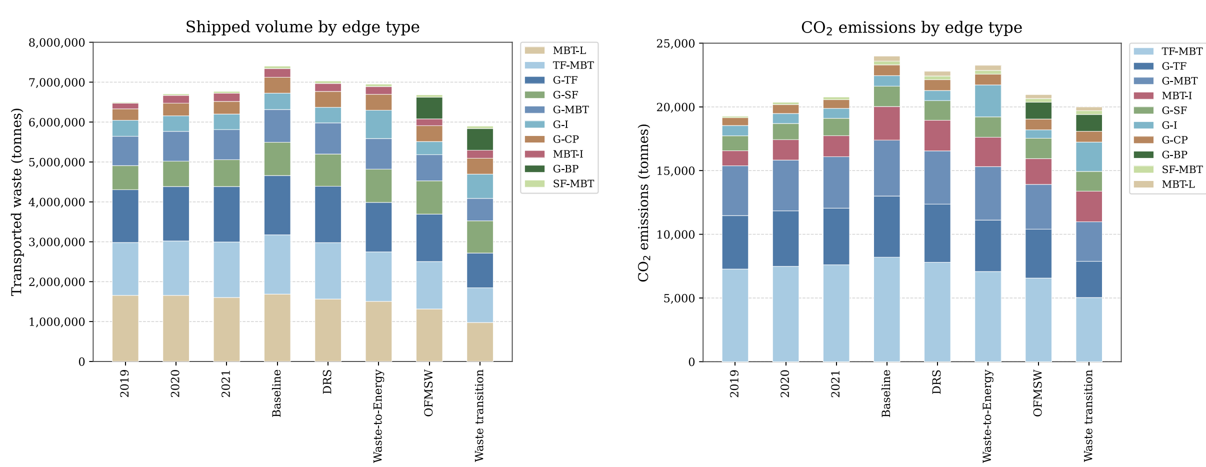


Fig. 7. Transferred waste volumes in regional Municipal Solid Waste (MSW) management optimized based on transport distance within the current Hungarian MSW network topology (2021). Ribbons indicate the ratio of settlements or facilities that would have shorter transport paths by diverting waste to processing facilities in neighboring regions (represented by outer arcs and colors) instead of adhering to within-region transport rules. Inner arcs represent the origin regions, outer arcs the destination regions, and the thickness of the ribbons indicates the proportion of waste flows. For instance, in the G-MBT layer, approximately 80% of settlements in region T could benefit from shorter routes to MBTs in region EK.



(a) Total transported volume per MSW fraction

(b) Total CO_2 emissions per MSW fraction

Fig. 8. Transported volumes and CO_2 emissions of Municipal Solid Waste (MSW) fractions in the network for the year 2021 and various scenarios in 2035.

presented in Fig. 8a. In 2021, the total transport volume was 6.77 Mt, which is projected to increase to 7.4 Mt by 2035 (Fig. 8a). The significant reduction in the amount of waste transported is due to the simplification of the network structure and highlights the fact that the impact of intervention at the source is reflected multiple times throughout the entire waste processing chain. In other words, this reduction is attributed to network simplification: if waste volume is reduced at the initial “G” (generator) nodes through source separation

Table 3
Total CO_2 emissions from municipal solid waste management on the basis of different types of actors and scenarios (in tonnes).

	2019	2020	2021	Baseline	DRS	OFMSW	Waste-to-energy	Waste transition
Biogas plant	–	–	–	–	–	35,984	–	35,984
Composting plant	145,452	161,178	160,826	202,394	202,394	202,394	202,394	202,394
Incinerator	685,989	737,535	747,432	792,529	745,225	626,768	1,141,408	1,019,870
Landfill	1,388,580	1,388,444	1,344,223	1,414,571	1,311,017	1,102,625	1,262,274	818,331
Transport	19,288	20,387	20,812	23,987	22,789	20,965	23,257	19,995
Total CO_2	2,239,309	2,307,544	2,273,293	2,433,481	2,281,425	1,916,768	2,629,333	2,024,606

and diversion, this positively influences subsequent stages (G-TF, TF-MBT, and MBT-L/I edges) by reducing total material handling and transport. The primary sequence of waste management treatment steps is $G \longrightarrow TF \longrightarrow MBT \longrightarrow I/L$.

The material flows for different edge types in the Waste Transition scenario are: G-TF and TF-MBT (cumulative 0.92 Mt), G-SF (0.81 Mt), G-MBT (0.51 Mt), MBT-L (0.5 Mt), G-I (0.61 Mt), G-CP (0.4 Mt), MBT-I (0.25 Mt), G-BP (0.54 Mt), and SF-MBT (0.06 Mt).

3.5. The carbon footprint of the Hungarian MSW management system

Table 3 summarizes the total carbon footprint of the MSW management system, grouped by actor type and scenario.

Table 3 indicates a slight annual increase in CO_2 emissions, projected to reach 2,433,481 tonnes by 2035 under the baseline scenario. In 2021, total emissions were 2,273,293 tonnes, with landfills accounting for 59.1% and incineration for 32.9%. Transport represented a comparatively small fraction at 0.9% of the total carbon footprint. It is important to note that the LCA impacts of recycling are not analyzed in this study, as it would require identifying specific LCA models for each material and technology, which is beyond the current scope.

The data demonstrate that diverting waste from landfills is the primary intervention for sectoral decarbonization, given that landfills are responsible for a significant portion of the total impact. However, for accurate impact identification, the entire network must be analyzed, as the interconnected material flows between different treatment facilities create substantial environmental loads. The total carbon footprint of the Hungarian MSW management system, modeled through the edges of the proposed network representation, is shown in Fig. 9, expressed in $CO_{2eq.}$.

Fig. 9 shows that in 2021, the entire sector generated 2.3 million tonnes (Mt) of CO_2 emissions. The prediction model projects an additional increase of 160,188 tonnes by 2035 under the baseline scenario. Increasing the proportion of waste incineration (e.g., 300,000 t of MSW in the WTE scenario) is expected to result in an increase of approximately 195,852 t of CO_2 emission. While incineration is generally less favorable in terms of EoL LCA impact compared to other valorization methods, it simultaneously reduces transported quantities and contributes to diversifying Hungary's energy mix.

The DRS scenario, aimed at recovering clean, separated waste, can reduce the carbon footprint by 152,056 t, with co-benefits for material reuse. Separating the OFMSW (kitchen waste) can reduce the volume of mixed MSW by approximately 20% (based on Hungarian MSW composition). This approach achieves CO_2 savings of 516,713 t and alleviates the burden on other treatment technologies. From an LCA perspective, biomethane production is the most favorable EoL solution, making the OFMSW scenario the most promising for transforming the MSW management system and reducing the carbon footprint. The joint implementation of all three scenarios (Waste Transition) results in 408,875 t of carbon footprint savings. This outcome is driven by changes in the distribution and treatment of transported waste quantities. However, in Fig. 9, the CO_2 footprint of the Waste Transition scenario is less favorable than that of the individual DRS and OFMSW scenarios. This is primarily due to the higher CO_2 footprint associated with the WTE component. This finding underscores the necessity of designing and developing MSW management systems that consider not only the carbon footprint but also overall system pressure and capacity.

3.6. End-of-life hotspots in the Hungarian MSW system in 2035

Fig. 10 depicts the incoming MSW volumes at the four types of end-of-life (EoL) treatment facilities within the network for the Waste Transition scenario in 2035.

These subplots clearly reveal significant spatial imbalances in the MSW system, with Budapest, as the capital city, exerting a considerable influence on this imbalance. This is partly linked to Hungary's historically star-shaped transportation system, centered around Budapest. Key characteristics for each EoL actor are as follows:

- **Biogas Plants (BP)** (Fig. 10 subplot a): The most significant structural change is projected for biogas plants. By 2035, a relatively high number (72) of new facilities will be involved in waste handling, with a total volume exceeding 543 kilotonnes (kt). The highest volume (18% of the total) is concentrated near Budapest. The geographical distribution of facilities generally ensures that no other large hubs are needed.
- **Composting Plants (CP)** (Fig. 10 subplot b): Composting plants will utilize kitchen waste, handling close to 400 kt in the final scenario, a 26% increase from 2021. Similar to other outputs, the highest volume (70 kt; 18% of total) is near the capital. Other large facilities are strategically located near highways and regional centers.
- **Incinerators (I)** (Fig. 10 subplot c): Incineration capacity is highly concentrated, with the two largest facilities (460 kt and approximately 200 kt) located near Budapest. The second facility is a new addition, indicated by a green dot. These two facilities collectively process 80% of the total incinerated waste. Future expansion should target western and southeastern Hungary to better utilize energy generation potential and reduce transportation costs.
- **Landfills (L)** (Fig. 10 **subplot d):** A major policy-driven change is the projected decrease in landfilled waste. The original 1.6 Mt in 2021 is reduced to 1.35 Mt in the 2035 baseline scenario due to DRS implementation. With additional measures in the Waste Transition scenario, the amount of landfilled waste is only 31% of the 2021 volume, reaching a final value of 501 kt. Of 37 potential landfill locations, 21 are utilized, mainly due to the limited number of intermediate mechanical biological waste handling facilities with nearby treatment options. The spatial distribution of operational landfills is fairly good. Hejőpapi (92 kt) handles the highest volume, serving as the main waste collection region for northeastern Hungary, followed by a plant near the capital (85 kt).

The isolines in Fig. 10, akin to topographic maps, connect points with equal incoming waste values for different EoL actors. Circular isolines suggest comparable facility attributes within a region (e.g., biogas plants in central and eastern Hungary). Increased density of these lines indicates significant changes in waste quantity and dissimilarity among regions, as evident for incinerators, where two major centrally located units dominate the landscape.

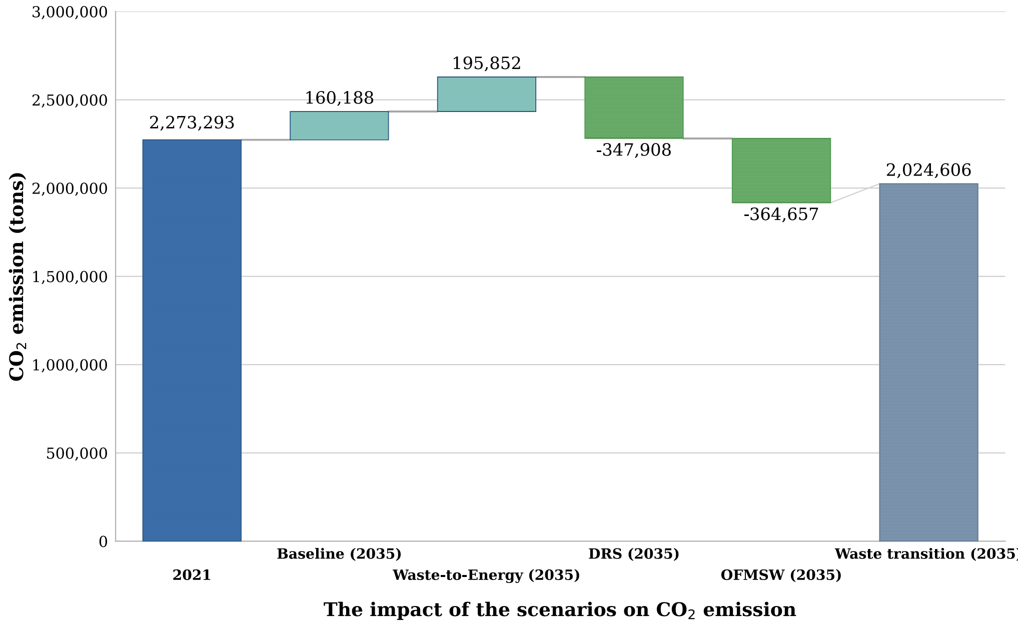


Fig. 9. Total CO_2 equivalent emissions for the analyzed Municipal Solid Waste (MSW) management system scenarios. The bars represent the total emissions for the baseline year (2021) and various policy scenarios projected for 2035, highlighting the relative impact of each strategy.

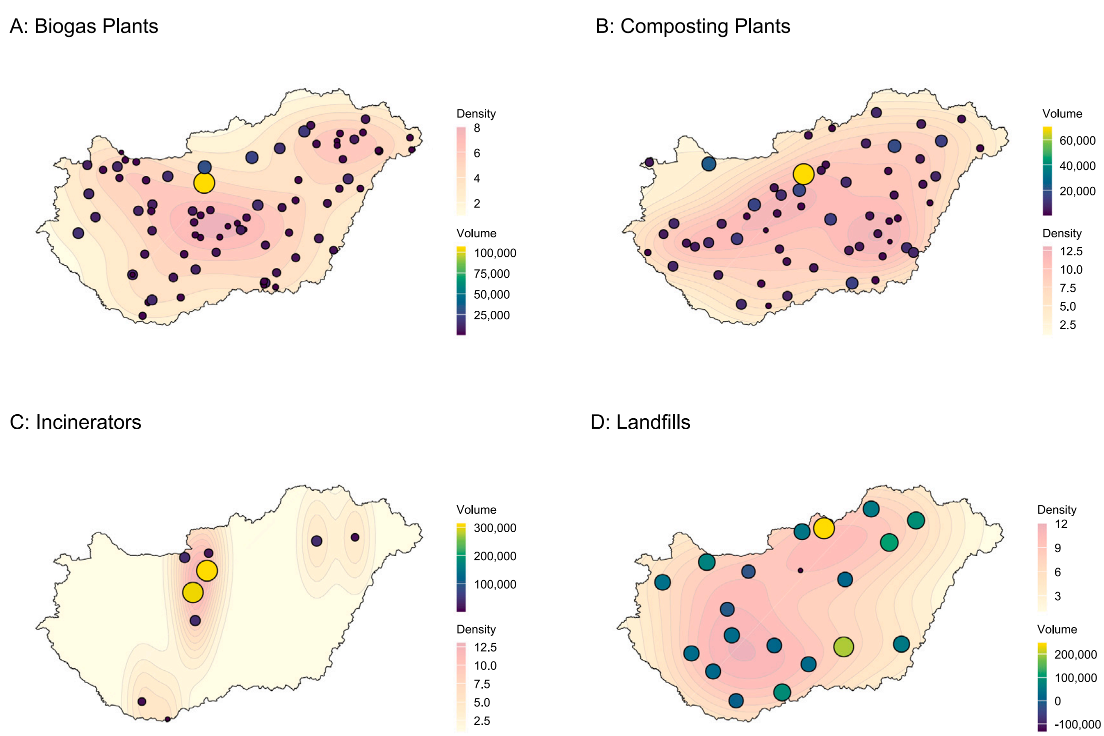


Fig. 10. Incoming waste volumes (in 1000 kg) by End-of-Life (EoL) handling type for the 2035 Waste Transition scenario. Subplots illustrate: (a) Biogas Plants (BP), (b) Composting Plants (CP), (c) Incinerators (I), and (d) Landfills (L). Node sizes are proportional to incoming waste volumes. Isolines connect points of equal incoming waste values, revealing geographical distribution and density of waste processing.

4. Discussion

This study successfully constructed a directed dynamic multilayer network (DMN) (Fig. 3) encompassing key stakeholders (Table 6) and their interactions within the Hungarian MSW management system (Fig. 2). This achievement represents a significant contribution (C_1), addressing a gap in MSW scenario modeling by providing a comprehensive network representation that tracks material flows across various treatment stages and over time. Unlike traditional approaches, our DMN allows for granular analysis of each waste type's treatment, optimizing processes in separate layers (Table 2) and enhancing predictive accuracy. This yields detailed, settlement-level estimates for the evolution of waste types under different scenarios and their associated environmental impacts, particularly from transportation.

The scenarios analyzed were grounded in actual Hungarian government and EU legislation (Fig. 4), providing a realistic assessment of policy interventions (C_2). We aimed to determine if these policies and directives could achieve the 2035 EU targets. The DMN proved invaluable for assessing policy impacts more comprehensively than traditional methods. Our network analysis (Figs. 5 and 7) revealed significant opportunities for optimizing transport routes and, consequently, reducing CO_2 emissions from transportation (C_3). The analysis indicated that vehicles in the eastern region of Hungary traverse the longest distances (Fig. 5), primarily due to a deficit of local processing plants (Fig. 6.f,g). Furthermore, waste is often not routed to the nearest processing facility or even to a designated plant within the same region, leading to suboptimal transport distances (Fig. 7 and Table 7).

Our findings, however, indicate that the currently proposed measures, even if fully implemented, may be insufficient to meet the desired EU objectives (Table 3, Figs. 9, 10). This highlights the critical need for a synergistic approach that simultaneously considers multiple objectives, such as waste reduction and decarbonization. Distinct scenarios must be designed with these factors in mind, as demonstrated by the varied outcomes in transported volumes and CO_2 emissions (Figs. 8–9). For instance, while the Waste-to-Energy scenario contributes to energy diversification, its higher LCA-based CO_2 footprint can diminish the overall decarbonization potential of an integrated strategy.

The DMN method allows for the identification of geographical areas where CO_2 emission reductions are particularly challenging, even with improved routes and new processing facilities. These include parts of the western region and the vicinity of Budapest, primarily due to existing infrastructure and urban density. Our study suggests that even with a five-year extension to 2040, Hungary's proposed measures may not fully achieve EU targets. Nevertheless, the developed methodology provides a robust tool for assessing the effects of future governmental initiatives, such as enhanced textile waste management or mitigation of improper disposal practices. Our analyses also revealed that while landfilling decreases, it does so at a slower rate than the increase in overall waste generation. Factors like the proliferation of packaging-free shopping, though not explicitly modeled, can be integrated into future analyses using this network logic.

4.1. Comparison of LCA measures

The comparative assessment of additional life cycle analysis indicators is presented in Fig. 11, where the year 2021 forms the basis (100%) for all impact categories.

The calculated LCA indicators for 2021 are as follows: Global Warming Potential (GWP) is 2,273,293 $tCO_{2eq.}$, Ecotoxicity freshwater total (Ecotox.)135,488,831 $CTUe$, Eutrophication freshwater (Eutroph.) 85 $\mathrm{kg}P_{eq.}$, Land Use 79,076,285 Pt, Particulate matter (PM) 0.33 $Disease\ \ incidences$, Resource use fossils (Fossils) 189,185,699 MJ, and Water use (Water) 252,684 $\mathrm{m}^3 world_{eq.}$. Based on Fig. 11, it can be seen that by introducing the measures of the "Waste Transition" scenario together, improvements can be achieved in almost every impact category, or the unpleasant impacts of the expected increase in the amount of waste can be offset, with the exception of water use, where the introduction of the measures increases the LCA impact by approximately one and a half times.

4.2. Net Present Value (NPV) assessment of Hungarian waste management sector

In order to take into account the economic aspects, a Net Present Value (NPV) model was prepared, based on the year 2021. The costs adjusted for the inflation rate are summarized in Table 4.

The costs in Table 4 are expressed in million €, and composed of the following elements: transport 0.0335 €/tonkm, sorting 33.48 €/ton, incineration 125.56 €/ton, and landfill 66.96 €/ton. The inflation rate was set at 3%, while the discount rate was set at 8%. Based on the model, the net present value of the Hungarian waste management sector corresponds to 2851 million €.

5. Conclusion

This study developed and verified a novel methodology for representing municipal solid waste (MSW) management systems as a directed dynamic multilayer network (DMN), exemplified by the Hungarian MSW system. The network comprises ten distinct layers, encompassing all key actors from waste generation (municipalities) to various end-of-life (EoL) treatment facilities, including transshipment facilities (TFs), mechanical biological treatment (MBT) plants, selective waste sorting facilities (SFs), composting plants (CPs), landfills (Ls), incinerators (Is), and biogas plants (BPs). This detailed representation of waste fraction flows across network edges enables a granular analysis of system modifications. We analyzed the impacts of organic fraction of municipal solid waste (OFMSW) separation, deposit–refund system (DRS) implementation, enhanced waste-to-energy (WTE) strategies, and their integrated application.

Our findings reveal significant infrastructural inhomogeneities, suggesting that the Hungarian system, originally designed with a landfilling orientation, requires substantial transformation to achieve primary goals of increased recycling and biogas production while reducing landfilled waste. Given that disposal chains are often multi-stage, interventions in the early phases of the waste management process have magnified effects downstream. These impacts were comprehensively analyzed using a life cycle assessment (LCA)-based carbon footprint metric for both transportation and treatment processes.

The study underscores that MSW systems must be strategically designed to meet ambitious CO_2 reduction targets, considering future facility capacities and potential system pressures. This highlights that without integrated planning, the true contributions and trade-offs of different strategies cannot be accurately identified. While the proposed network model effectively maps MSW flows and their environmental impacts, it currently does not include detailed technological specifications of treatment facilities, nor does it explicitly model network resilience or allow for full topological optimization. Addressing these aspects in future research would be crucial for advancing towards a truly sustainable MSW management sector.

5.1. Implications for scholars

This study introduces a novel DMN approach for MSW management scenario analysis, offering a comprehensive and detailed understanding of waste flows and their environmental impacts, a level of detail not feasible with previous methods. Scholars can leverage this methodology to conduct similar analyses in diverse geographical contexts or explore various MSW management scenarios. The DMN structure, with its ten layers representing different actors and processes, facilitates a nuanced analysis of system modifications and their effects, making it particularly valuable for researchers studying the transition towards a circular economy in waste management.

The research findings highlight several critical areas for future investigations. First, the study reveals that current and proposed measures may be insufficient to meet EU MSW management targets by 2035 or even 2040, suggesting a need for more effective strategies. Scholars should therefore focus on developing more ambitious and impactful strategies. Second, the identification of spatial imbalances in the Hungarian MSW system, especially in eastern regions, necessitates further research into optimizing facility locations and transportation routes to minimize CO_2 emissions. Third, the study emphasizes the importance of integrated planning to balance CO_2 reduction goals

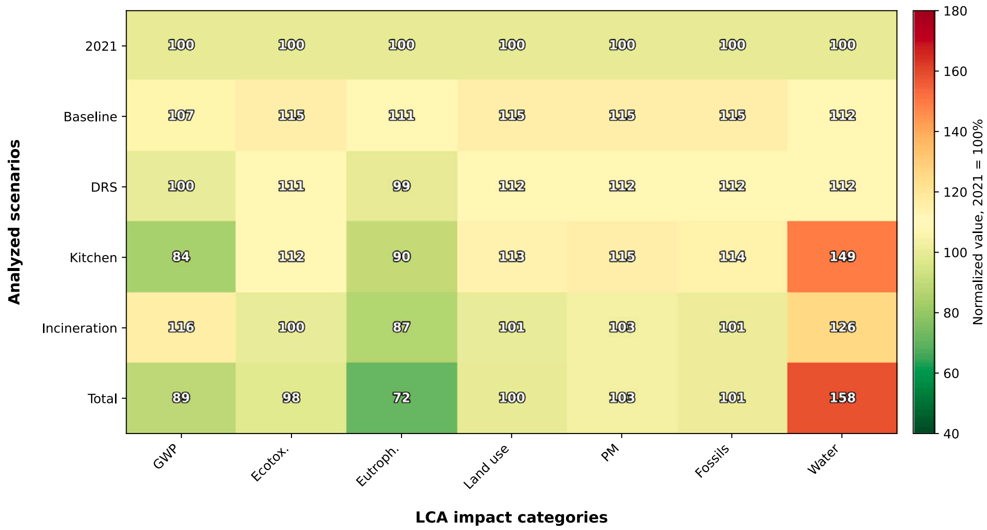


Fig. 11. Comparison of different life cycle assessment measures of the analyzed waste management scenarios in Hungary.

Table 4
Projected costs by waste management activity (2021–2035), million EUR.

	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035
Transportation	5.54	5.70	5.95	6.20	6.45	6.71	6.97	7.23	7.51	7.78	8.06	8.35	8.65	8.96	9.65
MBT sorting	71.83	74.20	77.13	80.08	83.07	86.11	89.21	92.37	95.61	98.92	102.32	105.80	109.38	113.06	116.83
Incineration	74.48	78.18	81.71	85.27	88.88	92.53	96.26	100.05	103.93	107.90	111.96	116.13	120.40	124.79	119.46
Landfill	107.42	106.58	108.32	110.18	112.16	114.24	116.42	118.71	121.09	123.58	126.16	128.84	131.62	134.49	170.98
Total cost	**259.26**	**264.67**	**273.12**	**281.74**	**290.56**	**299.59**	**308.86**	**318.37**	**328.14**	**338.18**	**348.50**	**359.12**	**370.05**	**381.29**	**416.92**

with future facility capacity requirements, advocating for a multiobjective approach to MSW system design in future research. Finally, the potential for further optimization of transport routes revealed by network analysis indicates that scholars should investigate advanced algorithms for route optimization in MSW management systems to further minimize environmental impacts.

5.2. Policy implications and action plan

This study provides several critical insights for policy-makers, particularly within the EU, concerning MSW management and decarbonization.

1. **Revise and Intensify Decarbonization Policies:** The research indicates that current Hungarian policies, even with full implementation of OFMSW separation, DRS, and WTE, are likely insufficient to meet EU waste management targets by 2035 or 2040. Policy-makers must acknowledge this gap and consider more ambitious, potentially synergistic measures to accelerate progress towards circular economy goals.
2. **Prioritize Integrated and Network-Based Planning:** The DMN approach highlights the interconnectedness of the MSW system. Policy-makers should adopt holistic, network-based planning tools to design strategies that optimize the entire system, preventing unintended consequences from isolated interventions. This includes considering both CO_2 reduction and future capacity requirements simultaneously.
3. **Address Regional Infrastructural Imbalances:** Significant spatial imbalances in MSW infrastructure, especially in eastern Hungary, lead to increased transportation distances and CO_2 emissions. Policies should encourage a more balanced distribution of waste management facilities and promote regional cooperation to optimize resource utilization and minimize environmental impact across all Member States.
4. **Incentivize Early-Stage Waste Diversion:** The analysis demonstrates that interventions at early stages of waste management (e.g., source separation of OFMSW) have magnified positive impacts throughout the system, leading to network simplification and reduced overall transport. Policy should strengthen incentives and infrastructure for household and commercial source separation to maximize benefits.
5. **Integrate Multi-Criteria Decision-Making:** The trade-off observed in the Waste Transition scenario (where WTE contributes negatively to overall CO_2 reduction despite other benefits) underscores the need for multi-criteria decision-making. Policy-makers should evaluate strategies not only by their decarbonization potential but also by other factors such as energy security, resource recovery, and social acceptance.

We believe that spatial and temporal MSW network representation, as demonstrated, offers a breakthrough in waste management planning. It is uniquely suitable for the ex ante identification of effects stemming from real-world, legislative-driven, and policy-based scenarios involving various system modifications, thereby enabling more informed and effective policy interventions.

5.3. Limitations and future work

Limitations of this study include the exclusion of cost modeling, which is crucial for full economic feasibility, and the lack of explicit modeling for institutional constraints that might affect policy implementation. Furthermore, detailed LCA models for each useful material and recycling technology were beyond the scope, potentially underestimating the full benefits of resource recovery. The current model also does not incorporate dynamic technological specifications of treatment facilities, which would be essential for assessing network resilience and deeper topological optimization. Cost-based optimization was also not the aim of this research, as the primary goal was to demonstrate the benefits of network-based representation and to present CO_2 emission

Table 5
Dataset structure for the Dynamic Multilayer Network (DMN) model, detailing the types of data collected, their descriptions, formats, and sources. This table provides an overview of the information used to build and analyze the Municipal Solid Waste (MSW) management system in Hungary.

Id	Section	Column name	Short Description	Format	Dataset used
1	Network	From	Node ID of an actor (municipality, etc.) as the starting point of transport.	String	NEIS, MOHU
2		To	Node ID of an actor (municipality, etc.) as the endpoint of transport.	String	NEIS, MOHU
3		Dist.	Road distance in meters between the two endpoints defined in columns 1 and 2.	Double	OpenStreetMap
4		Type	Type of edges based on the endpoint actors.	String	NEIS, MOHU
5 ⋮ 20	Weights	2006 ⋮ 2021	Transported waste amount via a specific edge.	Double	HCSO
21 ⋮ 33	Prediction	2022 ⋮ 2035	Prediction of waste amount based on historical data.	Double	HCSO
34	Scenarios	2035_Baseline	Predicted amount for each edge without adjustment related to any known scenario plan.	Double	HCSO, NEIS
35		2035_OFMSW	Predicted amount for each edge with adjustment based on the OFMSW (organic fraction of municipal solid waste) waste management plan.	Double	HCSO, NEIS
36		2035_DRS	Predicted amount for each edge with adjustment based on the DRS (deposit–refund system) waste management plan.	Double	HCSO, NEIS
37		2035_WTE	Predicted amount for each edge with adjustment based on the "waste-to-energy" waste management plan.	Double	HCSO, NEIS
38		2035_WT	Predicted amount for each edge considering the execution of all three waste management plans.	Double	HCSO, NEIS

changes of real planned or implemented policy interventions. These areas present promising avenues for future research to foster a truly sustainable MSW management sector.

CRediT authorship contribution statement

Attila I. Katona: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Zsolt Szigetvári:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Csaba Hegedűs:** Writing – review & editing, Writing – original draft, Validation, Methodology, Formal analysis, Conceptualization. **Zsolt T. Kosztyán:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Róbert Kurdi:** Writing – review & editing, Validation, Resources, Project administration, Funding acquisition, Data curation, Conceptualization. **Viktor Sebestyén:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Table 6
Node types, corresponding colors in visualizations, and total counts of each actor type within the Hungarian Municipal Solid Waste (MSW) management network (2021).

Node type	Color	Description	Count
G	Gray	Waste generation (municipalities)	3154
TF	Blue	Transshipment facilities	45
MBT	Yellow	Mechanical biological treatment facilities	23
SF	Purple	Selective waste sorting facilities	56
CP	Dark green	Composting plants	60
BP	Light green	Biogas plants	77
L	Brown	Landfills	37
I	Red	Incinerators	11

Appendix A. Structure and waste stream tables

The structure of the constructed dataset is shown in Table 5.

The columns of the edge dataset are organized into four main sections: *Network*-related columns (describing edge origins, destinations, distances, and types), *Weights* columns (containing historical transported waste amounts), *Prediction* columns (showing forecasted waste amounts from 2022 to 2035 based on historical trends), and *Scenario*-related columns (providing edge-specific waste data adjusted for the Hungarian Waste Management Plan (Ministry of Innovation and Technology, 2021) and specific policy interventions).

Table 6 presents the actor details presented in Fig. 3.

Table 7 shows the cumulative CO_2 emissions of the material flows at the edges of the network on the basis of edge type and scenario in tonnes.

Appendix B. ARIMA and logarithmic model forecast scenarios

See Fig. 12.

Table 7
Cumulative CO_2 equivalent emissions associated with material flows across different edge types for various Municipal Solid Waste (MSW) management scenarios (in tonnes). The values reflect emissions from transportation and treatment processes for the baseline years and projected scenarios for 2035.

Edge type	2019	2020	2021	Baseline	DRS	OFMSW	Waste-to-Energy	Waste transition
G-MBT	3,908	3,985	4,040	4,394	4,179	3,515	4,195	3,102
G-TF	4,198	4,356	4,445	4,799	4,565	3,839	4,038	2,844
TF-MBT	7,271	7,485	7,606	8,203	7,803	6,563	7,077	5,036
G-SF	1,174	1,266	1,362	1,600	1,549	1,600	1,600	1,549
G-CP	618	704	688	847	847	847	847	847
MBT-L	12	21	25	394	364	306	394	298
MBT-I	1,179	1,605	1,649	2,631	2,403	2,021	2,306	2,403
SF-MBT	120	179	213	293	293	293	293	293
G-I	808	785	782	826	786	661	2,509	2,303
G-BP	0	0	0	0	0	1,321	0	1,321
Total	19,288	20,387	20,812	23,987	22,789	20,965	23,257	19,995

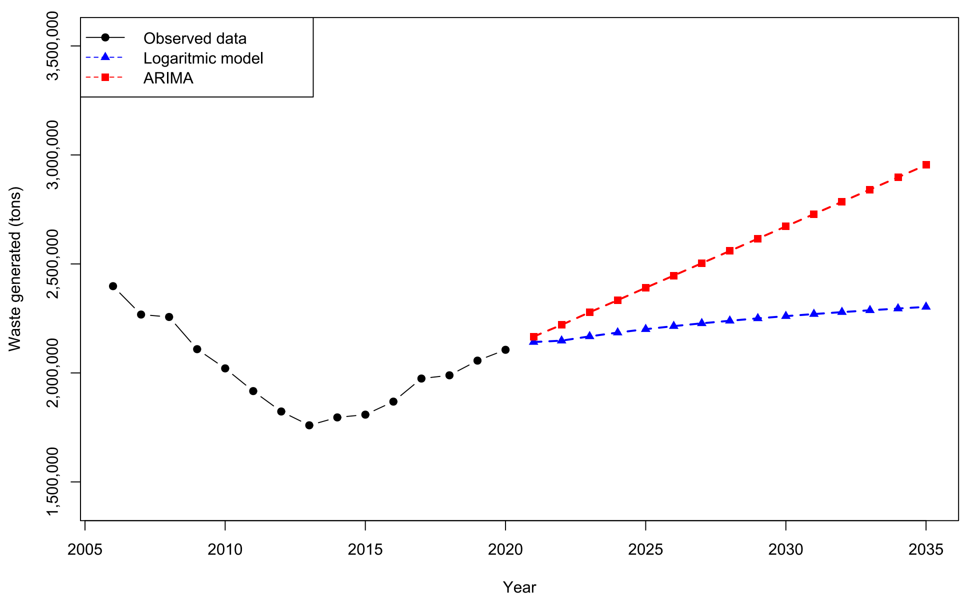

Fig. 12. Total waste amount forecast by ARIMA and logarithmic model.

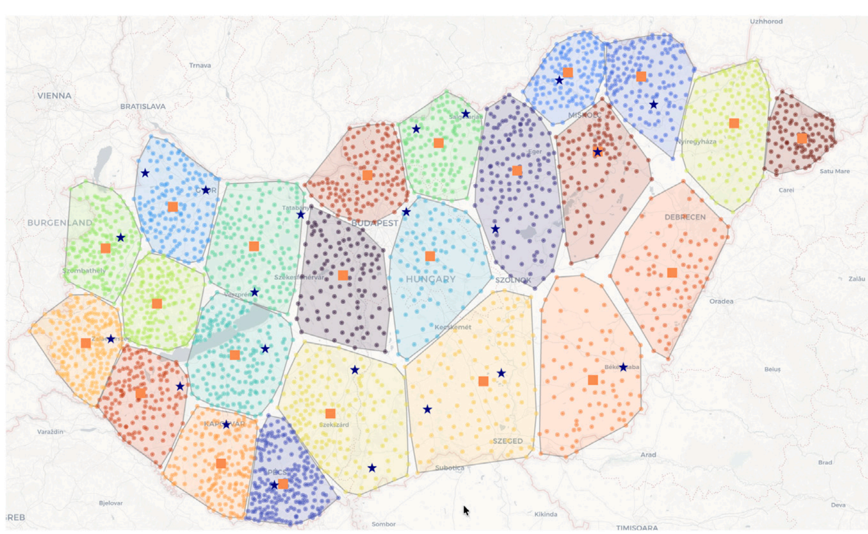

Fig. 13. Cluster centers (medoids) of the 23 clusters versus current MBT locations. Colored dots denote municipalities grouped by cluster; shaded polygons (concave hulls) delimit the spatial extent of each cluster; dark-blue stars (★) mark the current MBT facilities; orange squares (■) mark the k-medoid cluster centers.

Appendix C. Topology optimization

Fig. 13 shows the optimal locations of the MBT using k-medoid clustering based on the distance matrix between municipalities. The cluster number is 23, which equals the current number of current MBT-s. The figure reveals that the Eastern part of Hungary lacks these facilities; therefore, the overall route will be long, especially in the case of MBT-I relations (see Fig. 6).

Comparing the cost-optimal medoids (orange squares) with the existing facilities (dark-blue stars) reveals a systematic spatial mismatch. In the densely served western and central regions several current MBTs lie close to their cluster medoid, whereas in the Eastern clusters the medoids fall well away from any existing facility. This indicates that the present network is not aligned with the geographic centers of waste generation, which increase the transportation and the associated emissions. Because the cluster count is fixed at 23 — identical to the number of operating MBTs — the comparison isolates the effect of facility location rather than facility number: the long Eastern routes are a placement problem, not a capacity-count problem. Consequently, relocating capacity (or re-prioritizing investment) towards the Eastern medoids offers the largest marginal reduction in total transport distance and should be the first possibility considered when redesigning the MBT topology.

Data availability

Data will be made available on request.

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