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AUTOMATIZIRANI SUSTAV PRIKUPLJANJA OTPADA

AUTOMATED WASTE COLLECTION SYSTEM

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SAŽETAK

Gospodarenje komunalnim otpadom predstavlja izazov suvremenog urbanog razvoja, osobito u kontekstu porasta količina otpada i zahtjeva za smanjenjem utjecaja na okoliš. Automatizirani sustav prikupljanja otpada (AWCS), temeljen na pneumatskom transportu otpada kroz zatvorenu cjevovodnu mrežu, predstavljaju moderno rješenje s potencijalom unaprjeđenja učinkovitosti i održivosti sustava prikupljanja. U radu se analiziraju tehnički, okolišni, ekonomski i organizacijski aspekti primjene AWCS sustava. Provedena je usporedba automatiziranog i konvencionalnog sustava prikupljanja otpada te su analizirana iskustva implementacije u urbanim sredinama. Rezultati ukazuju na prednosti AWCS sustava u pogledu poboljšanja higijenskih uvjeta, smanjenja prometnog opterećenja, povećanja kvalitete odvojeno prikupljenih frakcija i racionalnijeg korištenja urbanog prostora. Međutim, visoki investicijski i energetski zahtjevi upućuju na potrebu pažljivo planirane i selektivne primjene ovih sustava.

Ključne riječi: *automatizirani sustav prikupljanja otpada (AWCS); gospodarenje komunalnim otpadom; pneumatski transport otpada; održivost; sustavi prikupljanja otpada*

ABSTRACT

Municipal solid waste management represents a significant challenge for contemporary urban development, particularly in the context of increasing waste generation and the need to reduce environmental impacts. The Automated Waste Collection System (AWCS), based on the pneumatic transport of waste through a closed pipeline network, represents a modern solution with the potential to improve the efficiency and sustainability of waste collection systems. This paper analyses the technical, environmental, economic, and organizational aspects of AWCS implementation. A comparison between automated and conventional waste collection systems is carried out, and implementation experiences in urban environments are examined. The results indicate that AWCS offers advantages in terms of improved hygienic conditions, reduced traffic load, enhanced quality of separately collected fractions, and more rational use of urban space. However, high investment and energy requirements point to the need for careful planning and selective application of such systems.

Keywords: *Automated Waste Collection System (AWCS); municipal solid waste management; pneumatic waste transport; sustainability; waste collection systems*

Stručni rad / Professional paper

1. UVOD
1. INTRODUCTION

The development of modern society, marked by intensive urbanization and growth in production, results in a constant increase in the quantities of waste. Changes in consumption patterns, a rise in the standard of living and the concentration of the population in urban areas additionally burden existing waste management systems. At the same time, the available spatial and environmental capacities for its disposal are decreasing, which requires a systematic and technically grounded approach to planning.

According to the Waste Management Act (Official Gazette 84/21, 142/23), waste is any substance or object which the holder discards, intends to discard or is required to discard [1]. Such a definition encompasses a wide spectrum of materials with different properties, which is why the manner of handling a particular type of waste must be adapted to its physical, chemical and biological characteristics. Waste management includes the activities of waste collection, transport, recovery and disposal.

Although in the Republic of Croatia in recent years the greatest attention has been directed towards waste treatment and recovery, as confirmed by the construction of waste management centres [2], in more technologically developed countries increasing attention is being paid to the collection phase itself [3]. It is precisely in this segment that the application of automated systems comes to the fore, representing the highest level of technological development in the organization and implementation of waste collection. The manner in which collection is organized directly affects the quality of separate collection, the possibility of further recovery and the operating costs of the system. In urban environments, various models are applied – from the classic “door-to-door” system to more technologically advanced solutions.

This paper discusses the basic concepts related to waste and the waste management system, with an emphasis on the organization of collection and the analysis of an automated waste collection system as one of the possible models of application in urban areas.

2. POSTOJEĆI NAČINI PRIKUPLJANJA KOMUNALNOG OTPADA
2. EXISTING TYPES OF WASTE COLLECTION SYSTEM

2.1. SUSTAV "VRATA DO VRATA"
2.1. DOOR-TO-DOOR SYSTEM

Historically, the most common waste collection system has been the "door-to-door" system, which has proven effective in reducing the environmental impact of waste management systems [4]. Waste is collected directly from households, with each residential unit having its own container, or through shared containers used by residents of multi-apartment buildings and users of commercial premises.

Slika 1 *Prikaz spremnika za obiteljske kuće*

Figure 1 *Illustration of waste containers for single-family houses*

Waste collection in this system is organised according to a predetermined schedule. In most municipalities and cities, separate fractions are collected, most commonly mixed municipal waste, biowaste, paper and cardboard, plastic and metal, and glass, with the number of separately collected waste fractions depending on the locally established model.

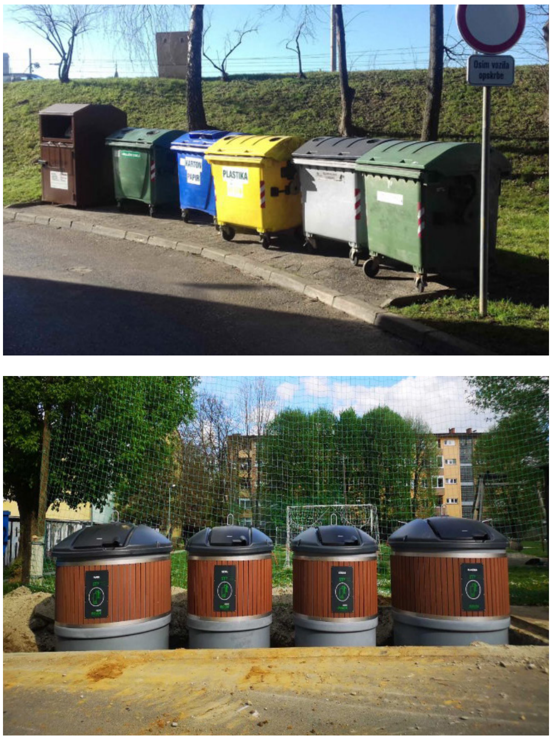
Most local government units already possess the necessary machinery and organisation for its implementation, so significant infrastructural adjustments are not required. The advantage of this model lies in the individualisation of users. The container is linked to a specific address and user, making responsibility for its contents direct and verifiable. This relationship encourages more careful waste sorting and enables the application of corrective measures and financial penalties in cases of improper handling [5].

Despite its widespread use and established organisation, this model requires a complex logistical structure. Its implementation involves numerous specialised vehicles that travel through urban areas daily, increasing the burden on the transport network. At the same time, the system generates considerable operational costs associated with labour, fleet maintenance, and fuel consumption.

2.2. SUSTAV ZAJEDNIČKIH SPREMNIKA

2.2. SHARED CONTAINER SYSTEM

In urban areas, the most common waste collection system involves residents of multi-apartment buildings using shared containers located near the waste disposal site. The containers most commonly found in cities are for mixed municipal waste, biowaste, plastic and metal, and paper and cardboard.



(a)

(b)

***Slika 2** Primjer (a) nadzemnih kontejnera [6] i (b) podzemnih kontejnera [7] za prikupljanje otpada*

***Figure 2** Example of (a) above-ground containers [6] and (b) underground containers [7] for waste collection*

The advantage of this model lies in relatively low initial investment, as a larger number of users share a limited number of containers. The system is particularly suitable for areas with a high turnover of residents and space users, where individual allocation of containers is not operationally efficient.

However, user anonymity negatively affects the quality of separate waste collection, resulting in a higher level of contamination within individual fractions. An additional challenge is service billing and the enforcement of penalties, as it is not possible to reliably link the quantity or composition of waste to a specific user.

In addition to conventional above-ground containers, underground systems are being installed with increasing frequency. Their use contributes to a tidier appearance of public spaces and reduces surface occupation at ground level. As a larger portion of the volume is located underground, the spread of unpleasant odours and the visual impact of waste on the surrounding environment are reduced. The disadvantage of this solution is the higher initial investment required for construction and installation.

3. AUTOMATIZIRANI SUSTAVI ZA PRIKUPLJANJE OTPADA (AWCS)

3. AUTOMATED WASTE COLLECTION SYSTEM (AWCS)

The waste management system comprises the interconnected stages of waste collection, transportation, treatment, and final disposal or recovery. Among these, collection and transportation are the most organisationally and financially demanding segments, directly affecting the functioning of urban areas.

The conventional model, which relies on above-ground and/or underground containers and collection by municipal vehicles, places a burden on the transport network, increases emissions and noise, and raises sanitary concerns in densely populated areas. In addition to high operational costs and the constant need for vehicle and labour deployment, opportunities for logistical optimisation remain limited [8].

To address these shortcomings, Automated Waste Collection Systems (AWCS) have been developed as a more technologically advanced solution. AWCS operate using a network of underground pipelines under negative pressure, through which waste travels from the point of generation to a collection station (terminal). This pneumatic and automated system enables improved management and control of the waste collection process. Beyond these advantages, the greatest benefits are improved hygiene and aesthetics, as waste collection truck traffic is eliminated from city streets and waste is transported through underground pipelines.

Slika 3 *Shematski prikaz automatskog sustava prikupljanja otpada (AWCS) [8]*

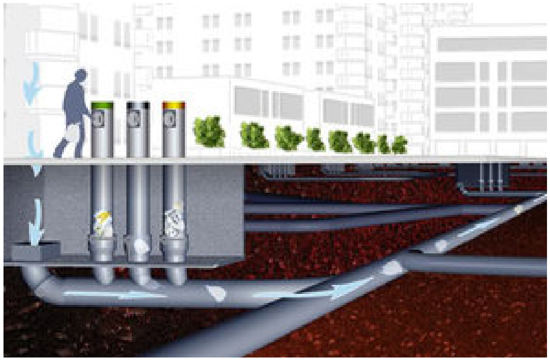
Figure 3 *Schematic representation of an automated waste collection system*

Such systems began to be developed in the 1960s in Sweden and have since spread worldwide [9]. They are most prevalent in Northern Europe, Spain, and the United Kingdom, as well as in countries undergoing intensive urban development, such as the United Arab Emirates, China, and Singapore [10].

3.1. KOMPONENTE SUSTAVA AUTOMATSKOG PRIKUPLJANJA OTPADA

3.1. COMPONENTS OF AN AUTOMATED WASTE COLLECTION SYSTEM

The pneumatic waste collection system consists of inlet stations (Figure 4a), a pipeline network (Figure 4a), and a central collection station—terminal (Figure 5), where all waste transported through the underground pipelines is collected and prepared for transfer to a recycling centre, waste management centre, or incineration plant.



(a)

(b)

Slika 4 *Ulazne stanice i podzemni cjevovodi (a) i sabirne stanice (b) [11]*

Figure 4 *Inlet stations and underground pipelines (a) and collection stations (b) [11]*

Inlet stations can be designed as external collection points or as waste disposal points within buildings. This approach is particularly suitable for large residential buildings with a high number of users [12]. The method of activating inlet stations varies depending on the city and system operator, but it is generally based on user identification through a card, electronic key, chip, or similar means. After successful authorisation, the appropriate opening for a specific waste fraction is unlocked, preventing incorrect disposal and the mixing of materials. This model enables precise monitoring of system usage and the quantities of deposited waste, while also encouraging greater individual user responsibility. Inlet stations are designed with an emphasis on integration into the urban environment and are more suitable in hygienic and functional terms than conventional above-ground containers, as they reduce unpleasant odours, waste dispersion, and contact with exposed waste contents [13].

Underground pipelines are most commonly made of steel due to its high mechanical resistance and ability to withstand the dynamic loads generated during the transportation of waste at high velocities [14] [8]. The diameter of transport pipelines in pneumatic systems generally ranges between 400 and 600 mm and is determined according to the estimated quantities and composition of waste conveyed through the system. In practice, a diameter of 500 mm is most commonly used, as it represents an optimal solution with respect to flow capacity and energy requirements. The air velocity must be sufficient to ensure the transport of solid waste to the terminal without accumulation within the pipeline. Under operational conditions, this velocity most commonly ranges from 18 to 25 m/s [5].

The most heavily loaded parts of the system are bends, joints, and pipeline intersections, as these are the points where changes in flow direction occur, leading to more pronounced abrasion of the pipe walls. The long-term effect of such loads can reduce the service life of the installation and increase maintenance requirements. An additional risk is posed by the disposal of waste not intended for transport through steel pipelines. Materials such as glass, due to their hardness and sharp edges, can cause significant mechanical damage to the internal surfaces of the pipes and accelerate system wear [14]. To reinforce critical sections, reinforced bends, large-radius bends, and additional protective coatings are incorporated into the design.

The depth at which pipelines are installed varies from 1.5 to 4 m depending on terrain conditions and the presence of other underground infrastructure. It is desirable for pipelines to be laid with gradients ranging from 0.5% to 2%, with the maximum recommended uphill gradient being 25% and the maximum downhill gradient 35% [8]. Since AWCS is often intended for city centres, as in the case of Bergen in Norway, the installation depth and routing of pipelines may also be influenced by archaeological sites.

Due to these technical challenges, inspection and sectional manholes are incorporated into the system. Inspection manholes provide access to the pipeline for regular inspections, monitoring the condition of installations, and carrying out interventions such as the removal of blockages or obstructions.

Sectional manholes segment the network, enabling the isolation of a particular section in the event of a malfunction or blockage. This allows the affected part of the system to be temporarily taken out of operation, while the remainder of the network continues to function without interruption.

Slika 5 *Izvedba kontrolnih okna [15]*

Figure 5 *Construction of incpection manholes [15]*

The central collection station, or terminal, is the key component of the Automated Waste Collection System. Within this facility, machinery generates negative pressure, receives waste from the pipeline network, separates waste from the transport air, sorts waste into containers, compacts the waste, and filters the transport air before releasing it into the environment.

Negative pressure is essential to AWCS operation and is generated by powerful industrial turbines or fans that create an airflow of sufficient velocity and volume for waste transport. These drive units are sized according to the length of the pipeline network, the number of inlet stations, and the expected types and quantities of waste [13].

After transportation through the pipelines, a mixture of air and waste arrives at the central collection station, where these two components are separated. The most commonly used separation devices employ centrifugal force to separate solid particles from the air. The solid fraction is then transported, depending on its composition, into dedicated containers intended for a specific waste fraction [5].

The air that has been in contact with the waste is filtered to remove dust, fine particles, and unpleasant odours, thereby reducing environmental impacts and improving the quality of life for people living in the immediate vicinity of the central collection station [12].

In addition to the physical infrastructure and technical equipment, the communication network and integrated monitoring and control systems play a crucial role in the reliable operation of the system. Stable and efficient operation is ensured through the use of Programmable Logic Controllers (PLCs) [16], SCADA systems [17] for centralised monitoring and control, and databases that enable continuous analysis and optimisation of system performance.

3.2. OKOLIŠNI I EKONOMSKI ASPEKTI AWCS

3.2. ENVIRONMENTAL AND ECONOMIC ASPECTS OF AWCS

Compared to conventional waste collection systems, AWCS does not eliminate environmental impacts but rather alters their type, intensity, and spatial distribution [5] [10]. Implementing this system reduces unpleasant odours, contamination, and the presence of pests. Additionally, it lowers the population's exposure to harmful impacts and improves sanitary conditions in urban environments.

The main advantage of AWCS over conventional systems is the reduction of negative impacts associated with traffic. The number of waste collection truck trips is minimised, as are the impacts related to increased traffic congestion, noise, and vibrations caused by truck movement through urban areas.

Despite expectations for a more advanced system such as AWCS, the total emissions generated by the system itself are comparable to, or even greater than, those of conventional systems. This is due to the high electricity consumption required to operate the turbines that generate negative pressure within the pipeline network. Besides the electricity needed to create negative pressure, the production of pipeline materials, construction works, and equipment installation also represent significant environmental impacts [13].

Several authors [10] [13] have conducted economic analyses of the implementation of such systems in urban environments. These analyses concluded that the investment costs associated with constructing inlet stations, the central collection station (terminal), pipeline installation, and inspection chambers represent a significant economic barrier to the introduction of AWCS. Initial investments are several times higher than those required for conventional systems. In addition to the financial investment, system construction is both time- and space-intensive. Construction works may last several years (depending on the size of the project), and during this period uninterrupted traffic flow through the streets must be ensured [8] [13]. The cost of construction depends on the length of the pipeline network, burial depth, and the number of inspection chambers [12].

System management is designed so that operating costs are maintained at the minimum technically achievable level. The integration of automated control algorithms and a centralised supervisory control system enables continuous monitoring of operating parameters and dynamic adjustment of operating modes to actual system loads [3]. This reduces unnecessary electricity consumption and increases the overall energy efficiency of the system.

As electricity represents the dominant component of operating costs, the analysis of energy supply sources becomes a key element of the techno-economic and environmental assessment of the system. If electricity is generated from fossil fuels, the specific emissions of CO_2 and other pollutants significantly affect the overall carbon footprint of the system. Increasing the share of electricity generated from renewable energy sources reduces specific emissions per unit of consumed energy, thereby directly decreasing environmental impacts and improving the system's sustainability indicators.

By comparing conventional waste collection systems and AWCS, it can be concluded that conventional systems are more financially viable over shorter time periods, whereas AWCS is more cost-effective over the long term. Reduced traffic congestion, the release of public space, and improved public health are indirect benefits of such a system that are difficult to quantify but should not be overlooked.

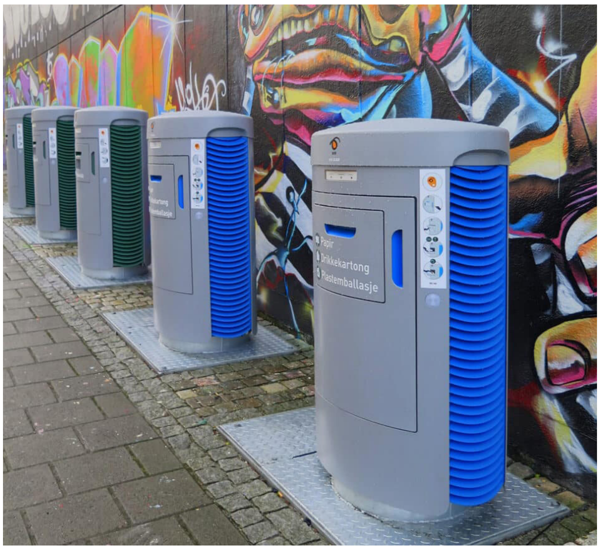
Although the system has its advantages, it does not in itself guarantee the achievement of circular economy objectives. The system's contribution depends on how it is integrated into the broader waste management framework. Therefore, the implementation of AWCS should be viewed as part of a broader strategy for sustainable development and the circular economy, with careful assessment of its overall technical, environmental, and economic impacts [8] [17] [13].

3.3. PRIMJERI IMPLEMENTACIJE AWCS SUSTAVA

3.3. EXAMPLES OF AWCS SYSTEM IMPLEMENTATION

A good example of the implementation of an Automated Waste Collection System (AWCS) in a historically and urbanistically sensitive context is the city of Bergen in Norway. As the second-largest Norwegian city and the site of a historic centre protected by UNESCO (the Bryggen district), Bergen faces challenges associated with narrow medieval streets, wooden architecture, and strict cultural heritage preservation requirements [18]. These conditions prompted the development of an underground pneumatic waste collection system that significantly reduces truck traffic, noise, and emissions in the city centre.

The system began development in 2007, coordinated with other infrastructure projects such as the reconstruction of utility installations and transport infrastructure, thereby reducing costs and the impact of construction works on the historic centre. The main obstacles were high investment costs, complex underground utilities, and the need to comply with conservation requirements. Despite these challenges, the project was gradually expanded and now covers a large part of the city centre, resulting in a significant reduction in the number of waste collection trucks and an improvement in the urban quality of the area.



Slika 6 *Ulazne stanice u gradu Bergenu, Norveška [19]*

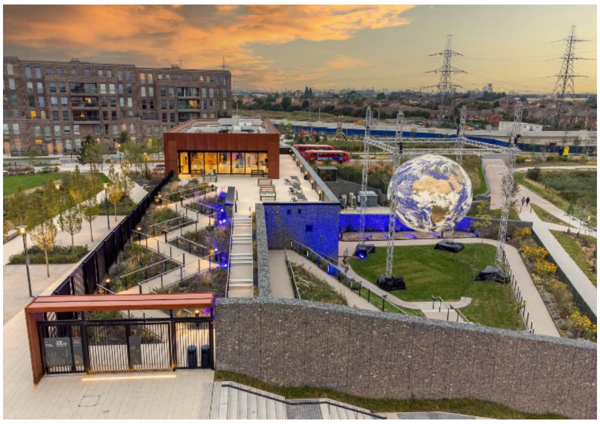
Figure 6 *Inlet stations in the city of Bergen, Norway [19]*

Currently, the AWCS in Bergen collects four separate waste fractions, with more than 1,200 inlet stations and 7,500 metres of underground pipeline network constructed, while 30,000 households use the system daily [19].

The example of Bergen demonstrates that AWCS can be successfully integrated into historically sensitive urban areas, provided that long-term planning, phased implementation, and strong institutional support are ensured.

In addition to Bergen, an excellent example of a brownfield investment incorporating an AWCS is the Barking Riverside district in East London. This project aimed to transform the site of the former Barking Power Station on the northern bank of the River Thames, which ceased operations in 1981, into a new urban district developed according to the principles of sustainable development and affordable housing for residents [20].

Part of the project is also an AWCS that collects three separate waste fractions. A total of 460 inlet stations have replaced 19,000 conventional waste containers, and 16 tonnes of waste are transported daily through underground pipelines. The central collection station of the AWCS is located on the ground floor of The Wilds Centre, a building intended for community events, situated in close proximity to the residential buildings of the district.



***Slika** 7 The Wilds Centre – Barking Riverside- London [21]*

***Figure** 7 The Wilds Centre – Barking Riverside- London [21]*

3.4. OGRANIČENJA POSTOJEĆIH ISTRAŽIVANJA I IDENTIFICIRANE PRAZNINE U ZNANJU

3.4. LIMITATIONS OF EXISTING RESEARCH AND IDENTIFIED KNOWLEDGE GAPS

A review of the available literature indicates that the technical, environmental, and economic aspects of Automated Waste Collection Systems (AWCS) are significantly dependent on the local context, particularly population density, pipeline network length, number of waste fractions, and the energy mix of the country in which the system is implemented. Life Cycle Assessment (LCA) studies confirm that the relative environmental advantage of pneumatic systems compared to conventional waste collection methods may vary depending on the source of electricity, with the share of renewable energy sources having a decisive influence on total greenhouse gas emissions [13] [8]. Although such analyses exist, their results are often linked to specific urban scenarios, which limits the transferability of conclusions to other spatial and infrastructural environments.

Economic analyses in the literature, including assessments of equivalent annual costs and comparisons of investment models, confirm that AWCS require substantially higher initial investments than conventional systems [22]. However, the heterogeneity of input assumptions – such as equipment lifespan, electricity prices, maintenance costs, and user density – makes it difficult to define universal thresholds of economic viability. The literature also frequently highlights indirect benefits, such as reduced truck traffic, the release of public space, and improved sanitary conditions, but their quantification and incorporation into economic models have not yet been methodologically standardised [5] [14].

Most published studies focus on highly urbanised environments in Northern Europe or on planned urban development zones, while medium-sized cities and transitional urban areas in Central and Southeast Europe remain underrepresented in scientific analyses. Given the differences in infrastructure capacities, financial resources, and organisational models, there is a need for context-specific evaluations to enable a more reliable assessment of the technical and economic feasibility of implementing AWCS under such conditions.

4. ZAKLJUČAK

4. CONCLUSION

The analysis of existing municipal waste collection models shows that the collection phase significantly determines the technical efficiency, costs, and environmental performance of the entire waste management system. The "door-to-door" system provides a high level of individual responsibility but generates increased traffic burdens and significant operational costs. The shared-container model requires lower initial investment; however, reduced user control negatively affects the quality of separate waste collection.

Automated Waste Collection Systems (AWCS) represent a more technologically advanced solution in which waste transport is transferred to underground infrastructure, thereby reducing traffic, noise, and the visual burden on urban areas. Although investment costs are considerably higher, long-term operational savings can be achieved and sanitary conditions improved. The overall environmental performance largely depends on the source of electricity and should therefore be assessed through a comprehensive Life Cycle Assessment (LCA).

The examples of Bergen and Barking Riverside demonstrate that AWCS can be successfully implemented both in historic city centres and in brownfield developments. In historically sensitive areas, the system enables the preservation of urban identity while simultaneously reducing traffic loads and emissions, whereas in new development zones it allows for the planned integration of municipal infrastructure from the outset of the project. Such experiences provide relevant guidance for the Republic of Croatia, particularly in the context of the restoration and revitalisation of historic urban centres, the redevelopment of former industrial complexes, and the construction of new residential areas. In such cases, the phased implementation of the system may be considered as part of a broader strategy for sustainable urban development.

The selection of a waste collection model must therefore result from a technical, economic, and environmental analysis adapted to the spatial and developmental characteristics of a particular area. Automated systems do not represent a universal solution, but in certain urban contexts they may constitute a justified and long-term sustainable infrastructure choice.

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• **Ivana Lovrić** - Ph.D., M.Sc. Eng. in Civil Engineering, was born in 1989 in Zagreb, where she completed her primary and secondary education. After finishing secondary school, she enrolled at the Faculty of Civil Engineering, University of Zagreb. Two years later, she began the Postgraduate Doctoral Study Programme in Civil Engineering at the same university, which she completed in 2025. She works as a lecturer at the Zagreb University of Applied Sciences, where she delivers lectures and practical classes in hydraulic engineering and courses related to environmental protection. Her main professional and academic interests are in hydraulic engineering. She participates in professional projects in hydrology and road drainage. She is married and has one child.

• **Šime Serdarević** - M.Sc. Eng. in Civil Engineering (Zadar, 1990), is a lecturer at the Zagreb University of Applied Sciences. At his institution, he teaches lectures and practical classes in Strength of Materials, Prefabricated Structures, Timber Structures, Earthquake Engineering, and Composite Structures. He is the author of approximately ten professional and scientific papers published in journals and conference proceedings in Croatia and abroad. He has published peer-reviewed teaching materials for a course he teaches. He has supervised more than thirty students in preparing their graduate

and final theses. He is a licensed civil engineer for design and construction supervision. As a design engineer, he has prepared more than fifty main and detailed design projects for building structures constructed from various materials. His primary professional and academic interests include modelling procedures, calculation methods, and analysis of the behaviour of steel, timber, and reinforced concrete structures in building construction.

• **Klara Mihovilić -** B.Sc. Eng. in Civil Engineering (Zabok, 1999), graduated from the Environmental Engineering in Construction study programme at the Zagreb University of Applied Sciences. She has two years' experience in hydraulic engineering design. She is employed at REGEA (Regional Energy and Climate Agency) as a Junior Project Manager, where she participates in the implementation of EU-funded and national projects. In her role, she works within a multidisciplinary team focused on energy and climate topics, as well as the development and implementation of projects with regional and national impact.