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Smart City 4.0 as the concept of strategically managed sustainable urbanism

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Abstract

Background: Smart technologies serve as a bridge between strategic business goals and sustainable development, creating a synergy among the economic, environmental, and social dimensions of business and circular urbanism.

Purpose: The objective of this paper is to analyse the impact of implementing smart technologies on the economic benefits for an urban centre in a Central European Union state.

Study design/methodology/approach: The research employs an econometric model to predict financial savings (30%, 40%, and 55%) resulting from the implementation of smart technologies in waste management within a selected urban centre.

Findings/conclusions: The predictions confirmed the existence of a positive and growing trend in financial savings across all analysed areas, highlighting the economic benefits of smart technology adoption.

Limitations/future research: The limitations of the research consist of inconsistencies in the implementation of smart technologies in waste management across different municipalities within the analysed country. Future research could expand the research sample to multiple urban centres and countries after the introduction of legislation that incentivises the uniform adoption of current smart technologies and the publication of up-to-date implementation data. This would facilitate the development of sustainable strategic plans and decisions that are tailored to both national level and local needs of individual urban centres, offering effective and long-term solutions for sustainable urban development.

Keywords

Smart city 4.0, urbanism, sustainable management, waste management, green economy

Introduction

The current era of growing urbanism and dynamic technological progress poses challenges in the area of sustainable development and the effective management of urban systems. Strategic sustainable management is an essential tool for supporting managerial decisions that not only carefully consider environmental impacts but also enhance the engagement of individuals and enterprises in the area of corporate social responsibility (CSR). CSR is currently focused on environmental concerns and the development of sustainability branding (Pollak, et al., 2021), which is crucial due to its ability to influence all stakeholders involved (Világi, et al., 2022). Sustainable urbanism, therefore, creates opportunities for innovative enterprises to develop urban areas while simultaneously minimising the ecological impact of urbanisation with an emphasis on improving the quality of life for urban residents (MESR, 2018; MESR, 2019). This endeavour is enhanced within the Smart City 4.0 concept, where technological innovations and effective management contribute to the creation of intelligent solutions for sustainable and resilient urban development (Yigitcanlar et al., 2023). Technologies have become a key instrument in achieving sustainability and gaining a competitive advantage (Abdul et al., 2024). Modern technologies empower smart cities with the potential to enhance the quality of life, streamline service delivery, and support sustainability (Joyce & Javidroozi, 2024). The successful resolution of problems and challenges in urban infrastructure through smart technologies is based on the effective analysis of vast datasets generated by the urban environment (Fedushko, et al., 2020). The value of data trading continues to grow in parallel with the increasing data availability. The use of smart technologies significantly enhances the efficient collection, processing, and interpretation of large data volumes, thereby improving the accuracy and relevance of commercial information (Khurshudov, 2024). This integration of smart technologies with commercial analytical processes opens up new possibilities for enhancing managerial decision-making in commerce, information management, and the strategic management of sustainable development. Consequently, the implementation of smart technologies in industry, particularly in the production sector, is seen as a catalyst for technological development aimed at sustainable production by means of innovative technological procedures (Oláh et al., 2020; Cajková, et al., 2021). One of the key objectives of sustainable business within the Smart City concept is the support of sustainable supply networks. These networks encompass corporate resource management, waste minimisation, and environmentally responsible procurement (green sourcing). The onset of the health-economical coronavirus crisis at the beginning of the 21st century prompted many manufacturing companies to redefine their approach to product supply, integrating servitisation into their business model, which resulted in overall advantages across the whole value chain (Sadjadi, 2024). In general, with few exceptions, the more developed and prosperous a country is, the greater the proportion of its population that lives in urban centres (INESS, 2023) contributes to value creation, and experiences a higher level of urbanisation. In some countries, such as Australia, the Netherlands, and the United Kingdom, the degree of urbanisation reaches as high as 90% (Dzator, et al., 2022). Globally, it is estimated that 68% of the global population will reside in urban areas by 2050 (UN DESA, 2018), driven by the influx of investors and the creation of new jobs with higher value added in cities. The current economy demonstrates that human resources and their expertise are crucial factors significantly influencing innovative potential and thus the long-term business success (Slavkovic & Miric, 2024).

Despite the topicality of urbanisation, there are examples of its decline due to suburbanisation or the preservation of rural character. According to data from the European Commission, the number of Slovaks living in urban centres decreased by a quarter from 1990 to 2014 (INESS, 2023). Although urbanisation is progressing at a slow pace in Slovakia, leading urban centres are increasingly recognizing the potential of technological innovations to address complex challenges. They are investing in projects supporting the Smart City concept, which includes the implementation of intelligent infrastructures, effective transport management, energy sustainability, and digital platforms. Moreover, these projects emphasize the modernisation of waste management with the goal of achieving sustainable, intelligent, and economically viable urban development. Smart urban initiatives are gaining momentum globally, aiming to tackle major urban problems by harnessing the transformative power of digital technologies. However, despite these efforts, the pace of innovation seems to be much slower compared to the rapid changes driven by digital technologies in other industries (Jose & Rodrigues, 2024).

The analysis of scientific literature reveals that previous studies have primarily focused on mapping the knowledge area of the Smart City concept through bibliometric and scientometric analysis (Zhao, et al., 2019), assessing the smartness of cities in accordance with Smart City indexes by means of comparative regional analysis of the Visegrad Group (Neumannova, 2020), and examining the role of macro factors in evaluating the smartness of cities (Alderete, 2020).

Additionally, the research has explored the proposal of the new City 4.0 concept (Yigitcanlar et al., 2023), the technologies used for data collecting in smart cities (Khurshudov, 2024), the impact of Smart City initiatives on green economic efficiency (Chen, et al., 2024), and the impact of the COVID-19 on the realization of the Smart City concept, particularly through innovative procedures in waste management within sustainable intelligent mobility frameworks (Sadjadi, 2024). The aim of this study is to advance the understanding of the requirements for implementing smart technologies in waste management, analyse the outcomes of these technologies, and re-evaluate their cost-effective impact on a selected urban centre in the Slovak Republic, a member of the Visegrad Group.

1. Theoretical background

The strategic management of sustainable urbanism and the use of smart technologies contribute to the transformation of the urban environments towards smarter and more eco-friendly sustainable solutions, which address global challenges related to adaptation to climate change in the 21st century. Global cooperation in the realm of smart technologies is inevitable in the context of current environmental challenges (Fernandez-Anez, et al., 2018) and growing urban populations. According to Shin, Kim and Chun (2021), smart citizens not only comprehend digital technologies but also utilize them effectively to adapt to various systems of modern cities. Smart technologies, as an integral part of Smart Cities concept, encompass technological innovations designed to optimise and improve various aspects of human life and social functioning. Nowadays, the key concepts driving innovation in information systems are ‘intelligent’, ‘open’, and ‘network’, which enhance their potential and improve decision-making processes (Olah et al., 2020). At the beginning of the 20th century, only 13% of the global population lived in cities (Global Education, 2024). By 1950, this proportion increased to approximately 30% (UN DESA, 2014), and currently, it exceeds 50%, specifically 55% (Skills 4 cities, 2021; Global Education, 2024). This percentage is projected to reach 68% by 2050 (UN DESA, 2018). The population is categorized into those living in urban centres, urban clusters, and rural settlements (rural grid cells). According to the EU, urban centres are defined as contiguous areas with a minimum population density of 1,500 persons per square kilometre and a total population of at least 50,000 inhabitants (European Commission, 2016). In Slovakia, there are significant differences between the western and the eastern regions (Dorcak, et al., 2015). The category of urban centre comprises most of the territory of Bratislava, Kosice, Zilina, and Presov, while more than 96% of the population cells fall into the category of rural grid cells (INESS, 2023). Despite this fact, leading Slovak urban centres are investing in sustainable projects supporting the Smart City concept at every stage of its development.

1.1. Generation of smart cities and sustainable urbanism

The Smart Cities concept originated in the 20th century, in a period of significant technological progress in communication technology. The development of the ‘Smart Cities’ concept emerged from industry initiatives at the European level, leading to the formation of the ‘Smart Cities and Communities’ industrial activity. This initiative focused on integrating traffic and energy systems to reduce their environmental impact. A year later, the European Innovation Partnership on Smart Cities and Communities was established, incorporating information and communication technologies and providing a basic framework for the Smart Cities concept (Ministry for Regional Development of the Czech Republic, 2018).

Figure 1 presents an overview of the historical development of the Smart City concept in relation to its impact on waste management.

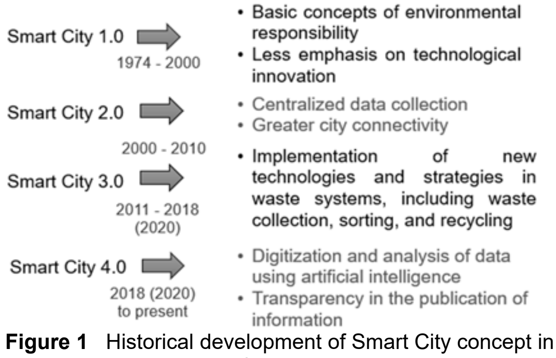

Figure 1 Historical development of Smart City concept in the context of waste management
Source: the authors

The following chapters provide a detailed description of each of the Smart City concepts based on the historical development.

1.1.1. First generation - Smart Cities 1.0

The first generation of smart cities, known as Cities 1.0, spans from 1974 to 2000 (Kumar & Singh, 2022). During this period, initiatives emerged focusing on using information technologies to enhance the quality of urban living conditions. This generation was characterised by the development of technology, data isolation, and decentralised innovation planning. Technology developers urged urban policymakers to adapt urban infrastructures to these technological solutions to achieve higher effectiveness in managing urban processes. Despite these efforts, many cities struggled to effectively use these technologies and correctly assess their impact on residents' quality of life, despite this effort (Human Smart City, 2019). Sustainable management during this early stage primarily focused on fundamental concepts of environmental responsibility with limited emphasis on technological innovations. The corporate sector and municipalities began to deal with issues such as resource efficiency in production and waste minimisation, though they largely relied on traditional methods of management. Municipalities actively tried to secure collection points for residents, where waste was typically transported to landfills or recycling facilities. Cities experimenting with new approaches to urban problems at that time laid the groundwork for the future development of smart cities.

1.1.2. Second generation - Smart Cities 2.0

The second generation of smart cities, known as Smart Cities 2.0, which developed until 2010, emphasized the integration of various information technologies to enhance the interoperability and efficiency of urban systems. Unlike the first generation, this phase was marked by widespread connectivity throughout entire cities and the centralised collection of large volumes of data. In this generation, municipal self-governance took a leading role in shaping the future of cities by implementing intelligent technologies and innovations. Cities actively supported a number of programs and projects integrating modern technologies into various aspects of municipal infrastructure and services (Paetsch et al., 2017; Human Smart City, 2019). The industrial growth of smart cities and urban networks was further driven by initiatives such as Smart City Expo and City Protocol (Fastcompany, 2015). Technologies were regarded as equally important as the human factor at this stage (Human Smart City, 2019). Sustainable management became increasingly focused on technological innovations and the efficient use of resources. Cities started implementing modern technologies and strategies into their waste management systems, including waste collection, sorting, and recycling. Through centralized data collection and enhanced connectivity, cities were better able to understand residents´ needs and optimise waste management systems, leading to more effective operations and reduced environmental impact. In this context, it can be stated that the transition of cities towards a bioeconomy will rely on progress in technology across a wide range of processes, achieving breakthrough in terms of technical performance and cost efficiency (Bikar et al., 2018).

1.1.3. Third generation - Smart Cities 3.0

The third generation, known as Smart City 3.0 (2011 – 2018) placed a significant emphasis on active civic participation in shaping urban environments (Giela, 2023). The development of participative platforms and applications enabled citizens to communicate with municipalities, express their opinions, and take part in decision-making processes. Social initiatives, such as promoting equality, social integration, and affordable housing, were also deemed significant in this period (Human Smart City, 2019). The European migration crisis, which peaked between 2015 and 2019 (Vasic et al., 2023), prompted many European cities to revise their policies and technologies to be able to respond to demographic changes and address problems related to an increase in waste.

The need to secure large volumes of information while protecting personal data became more pressing (Kumar & Singh, 2022). Crowdsourcing and open innovation enhanced participation between citizens and urban authorities, facilitating the development of innovative solutions for smart cities. This generation saw the promotion of sustainable practices among citizens, which enabled monitoring of individual waste habits and accessing information on proper sorting methods. Educational campaigns and events were organised to raise public awareness about environmental challenges and encourage sustainable lifestyles. The managers of sustainable policies focused on reducing the use of disposable products and promoting renewable and recyclable materials within the policies of sustainable shopping. Innovative approaches to managing organic waste, such as community composting (Alvarez-Alonso et al., 2023) and the adoption of biodegradable packaging materials, were also introduced. Support was extended to local enterprises producing environmentally friendly products and ecological mobility solutions, such as electric vehicles and shared transportation services. Concurrently, efforts were made to expand public green spaces (Gasser, et al., 2024). Cities also supported research and innovation to discover new and more efficient methods of waste processing. Technologies and strategies for collecting, sorting, and recycling waste were implemented together with using information technologies to enhance the efficiency and monitoring of waste management processes.

1.1.4. Fourth generation - Smart Cities 4.0

The generation of Smart City 4.0 (emerging since 2018, though some sources cite 2020) is a significant step in the evolution of smart cities, where technological innovations and digitalisation are seamlessly integrated into everyday life and functioning of cities. The adoption of advanced technologies, such as artificial intelligence analysis and process automation, are the characteristics and an integral part of this generation. Moreover, this generation emphasises transparency, which provides access to data and information for citizens, enterprises, and scientific organisations. Cities are investing in environmental solutions, such as intelligent energy systems, renewable energy sources, green buildings, or autonomous environmentally friendly transportation. The transformation also extends to the workforce, where new types of jobs require a fresh set of managerial competencies within the context of smart cities (Skills 4 cities, 2020). Not only are modern managers expected to possess technological knowledge and the ability to adapt to rapidly changing technological environments but they ought to have skills in data management, digital marketing, and interpersonal communication. This expanded skill set reflects the necessity to address the diverse challenges and tasks arising from the increasing influence of technologies on the workplace and society as a whole.

Rapid technological advancements and the Fourth Industrial Revolution have significantly reduced product life cycles and increased the complexity and unpredictability of consumer behaviour (Ubiparipovic, et al., 2023). This dynamic environment requires waste management companies to continuously adapt and change their practices.

The global health crisis, initiated by the COVID-19 pandemic in 2019, had a significant impact on the development of smart cities within the generation of Smart City 4.0. In response to the challenges posed by the pandemic, many companies decided to diversify their offerings and implement servitisation as an integral part of their business model (Sadjadi, 2024). This step aimed at maintaining sales and delivering added value to customers. New trends brought about by the COVID-19 pandemic, such as changes in customer behaviour, increased business flexibility, the rise of servitisation, remote work, or coworking places have a potential for the whole supply chain. Studies conducted during the lockdown period observed a decrease in air pollution in various cities (Sadjadi & Fernandez, 2023; Venter et al., 2020). However, the pandemic also led to panic purchases (Prentice, et al., 2020) and the closures of a substantial number of enterprises (Markovic et al., 2022), which contributed to a surge in food waste production during the first wave of COVID-19. There was a greater emphasis on hygiene, and the health and safety of the staff in waste collection facilities with the increase in healthcare waste, such as face masks, virus tests, disinfectants, and gloves.

During subsequent waves of the coronavirus pandemic, consumers focused on sustainability and adopted the “less is more” principle in their purchasing decisions (Ferreira et al., 2024), which differs significantly from pre-pandemic consumption patterns and trends (Brydges, et al., 2022).

This period brought significant changes to the business environment, making it ideal for innovation and transformation (Ferreira et al., 2024).

The outbreak of the pandemic underscored the need for the development of decentralised systems of waste disposal (Sadjadi, 2024). The implementation of automation and smart technologies in waste management has catalysed the optimisation of entire waste system and contributed to the development of the current generation of smart cities.

A detailed analysis and diagnosis of a firm´s financial situation serve as a “warning signal” for firms (Grosu et al., 2023) and reveals potential risks and opportunities that are crucial for the effective management of companies operating in waste management.

In the light of these considerations, the aim of this paper is to analyse the impact of implementing smart technologies on the economic benefits of a selected urban centre in one of the European Union countries that invest in smart technologies to promote renewable resources and sustainable urbanism. The focus of the present study will be answering the following research questions based on a literature review: *RQ1: What is the average resale value of selected secondary raw materials within the EU? RQ2: How do selected smart technologies affect the costs of waste management in the selected urban centre? RQ3: What are the projected financial savings in waste management in the selected urban centre?*

2. Methods

The research on waste management will use publicly available data from Eurostat (2022) covering the period 2015-2021 and data obtained from one of the major waste management companies operating in the Slovak Republic. The company operates in the sector classified as E38 - Collection, treatment, and disposal of waste and material recycling according to the SK-NACE sectoral classification. At the request of the analysed company, its name will remain anonymous. The data collected from the company will be analysed on a monthly basis, but for the sake of clarity, the results will be presented as quarterly data. The findings will be illustrated through bar charts, run charts, and tables.

The research will employ a statistical method using an econometric model, which will be processed in the EViews software. This model will be used to forecast the future economic savings resulting from the implementation of smart technologies in waste management in the selected urban centre.

3. Results and Discussion

3.1. Sorted Waste Components as an Exchange Commodity

Sorted waste is becoming an increasingly valuable commodity in the global market, contributing to the sustainable use of energy resources and reducing the environmental burden. Recyclable materials, such as plastics, paper, and glass, are finding new applications across various industries, thereby supporting the circular economy. These separated waste components hold not only environmental significance but also monetary value. The results section provides a summary of the sales value of the most common secondary raw materials, specifically paper, plastics, and glass, over the period from 2015 to 2021. Figure 2 presents the average sales value of sorted paper.

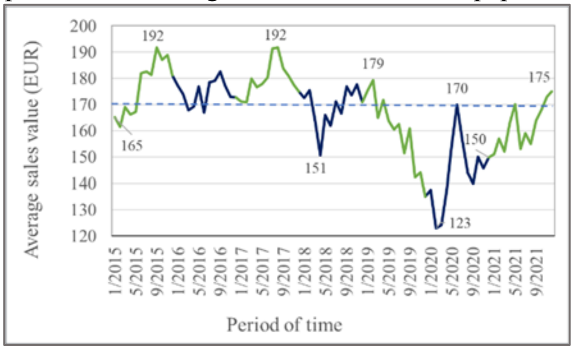

Figure 2 Development of exchange prices of sorted paper per ton
Source: Eurostat, 2022

As shown in Figure 2, the purchase price of recovered paper was EUR 165 per ton in January 2015, rising to EUR 175 per ton in December 2021. The median price over the entire period was EUR 170 per ton.

Figure 3 illustrates the average sales price of sorted plastics.

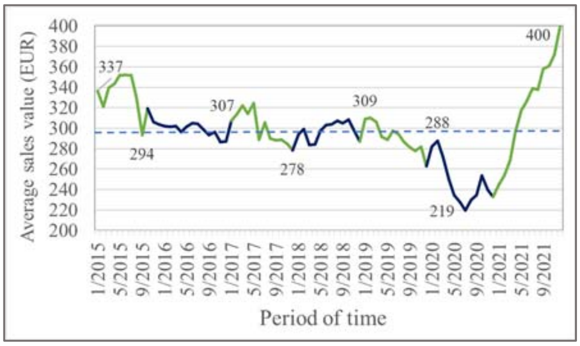

Figure 3 Development of exchange prices of sorted plastics per ton
Source: Eurostat, 2022

As seen from the data in Figure 3, the purchase price of plastics intended for recycling was EUR 337 per ton in January 2015, increasing to EUR 400 per ton by December 2021. The median price throughout the entire monitored period was EUR 298 per ton.

Figure 4 shows the average sales price of sorted glass.

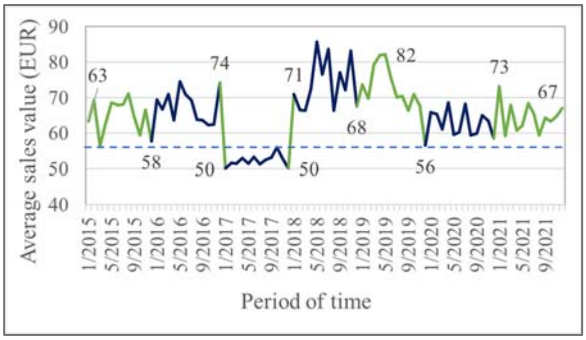

Figure 4 Development of exchange prices of sorted glass per ton
Source: Eurostat, 2022

Figure 4 shows that the average sales price of glass was EUR 63 per ton at the beginning of the monitored period (January 2015). The price increased to EUR 67 per ton in December 2021. The median price for the entire period was EUR 66 per ton.

3.3 Internal and External Cost Drivers of Individual Items in Waste Management

3.3.1 Distribution of Costs in Smart Technologies in the Slovak Republic

According to the study by Fedushko, Ustyianovych and Gregus (2020), the costs associated with implementing smart technologies in waste management can be divided into four categories: hardware, software, connectivity, and operation. Figure 5 illustrates the distribution of these categories in Slovakia in 2021.

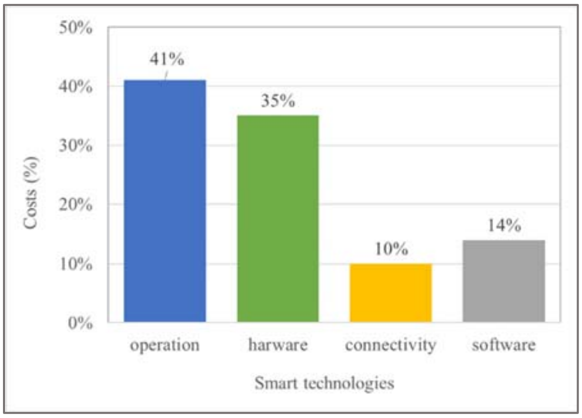

Figure 5 Distribution of Smart technologies by cost contribution in the waste management sector in Slovakia in 2021
Source: the authors

As shown in Figure 4, the largest cost item in the analysed period was the operation of waste management companies, accounting for 41% of the total costs. The second largest expense was cost of hardware (35%), followed by software (14%). The smallest cost item was the cost of network connectivity, which constituted 10% of the total costs.

3.3.2 Landfill Tax Dichotomy

In order to achieve the environmental targets established by the European Union, the Slovak government enacted Regulation 330/2018, which imposes various fees for waste disposal in landfills based on the degree of its sorting.

Figure 6 illustrates the percentage of sorted municipal waste in the period from 2019 to 2021 following the implementation of this regulation.

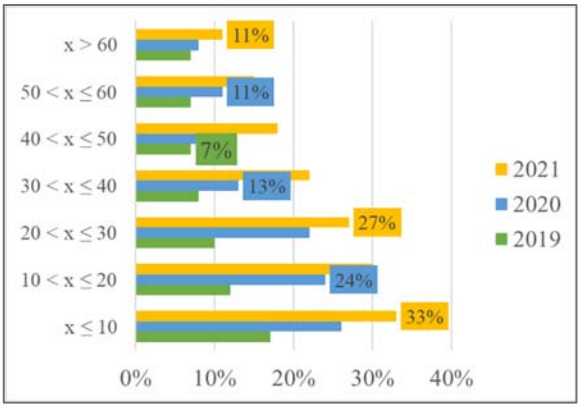

Figure 6 Level of municipal waste sorting
Source: the authors

As shown in Figure 6, the level of municipal waste sorting in 2021 increased compared to the year 2019. The percentage increase is detailed in Table 1.

Table 1 Level of municipal waste sorting

Level of municipal waste sorting in %	Percentage increase between 2019 and 2021
x > 60	157%
50 < x ≤ 60	214%
40 < x ≤ 50	257%
30 < x ≤ 40	275%
20 < x ≤ 30	270%
10 < x ≤ 20	250%
x ≤ 10	194%

Source: the authors

According to the data in Table 1, the average level of municipal waste sorting increased by 202.42% between 2019 and 2021. In 2019, municipalities that sorted 40% to 50% of their waste paid a fee of EUR 7 per ton. This fee rose to

EUR 12 per ton in 2020, and to EUR 18 per ton from 2021 onwards. The total increase in fees over this period was 257.14%. Through this regulation, the Slovak government aims to financially discourage municipalities from landfilling waste while incentivizing improved waste sorting and increased energy recovery.

3.3.3 Savings achieved through smart technologies in waste management

In the city of Nitra, the efficiency of waste collection has been enhanced by optimizing routes and adjusting the frequency of collection as needed. All bins are labelled and equipped with internal filling sensors. Nitra´s municipal services manage over 23,500 containers and handle approximately 49,000 tons of waste per year. The company reports a 30% reduction in waste collection thanks to these smart technologies.

In Šumperk and the adjacent municipality Rapotín, the application of smart sensors in bins and an inventory of collection bins resulted in a total cost saving of 53%. Specifically, the time needed for efficient collection was reduced by 58% due to improved utilization of the collection vehicle and its crew. Additionally, the frequency of collection decreased by 61%, resulting in less wear and tear on the superstructure and collection containers.

In the municipality of Dojč, automatic weighing of bins during waste collection and the implementation of quantitative collection with RFID chips resulted in savings in both main categories of waste. The generation of municipal mixed waste decreased from 250 tons in 2019 (before chips and weighing were implemented) to 179 tons in 2020, which represents a decrease by 28%. The waste sorting rate increased from 22% in 2018 to 36% in 2019 and exceeded 58% in 2020, marking a 36% increase over the three-year period under review.

3.4 Econometric Model and Calculation of Potential Savings with Application of Smart Technologies

3.4.1. Econometric Model

The econometric model calculations were performed using EViews software. The results are presented in Figure 7.

Dependent Variable: SALARIES
Method: Least Squares
Sample: 1 40
Included observations: 40

Variable	Coefficient	Std. Error	t-Statistic	Prob.
NUMBER_OF_EMPLOYEES	6689.338	164.0790	40.76901	0.0000
QUANTITY_ RESIDUAL_WAST	2.044168	0.602317	3.393839	0.0019
QUANTITY_ SEPARATE_WAST	-20.58769	7.662655	-2.686756	0.0115
SEPARATING_COSTS	0.161492	0.052577	3.071505	0.0044
INFORMATION_SYSTE_COSTS	0.129139	0.182308	0.708360	0.4840
PROFIT_FROM_SORTING	-0.191405	0.096680	-1.979766	0.0567
EMPLOYEES_SMART_TECH	853.4865	2360.736	0.363072	0.7190
FLEET_COSTS	0.007512	0.002641	2.844352	0.0078
C	-781149.5	63052.35	-12.38890	0.0000

R-squared	0.999830	Mean dependent var	2350372.
Adjusted R-squared	0.999786	S_D. dependent var	388573.8
S.E. of regression	5681.182	Akaike info criterion	20.32281
Sum squared resid	1.00E+09	Schwarz criterion	20.70281
Log likelihood	-397.4563	Hannan-Quinn criter.	20.46021
F-statistic	22801.88	Durbin-Watson stat	1.520518
Prob(F-statistic)	0.000000		

Figure 7 Output from the EViews software – sorted data
Source: the authors

The results shown in Figure 7 indicate that the probability (F-statistic) is less than 5 %, which means that the model is statistically significant.

In the econometric model, the variables with the greatest impact on labour costs are the Number of employees (coefficient 6689) and Employees for smart technology (coefficient 854). Other variables influencing labour costs include the Quantity of municipal waste (coefficient 2), Sorting costs (coefficient 0.16), Cost of information systems (coefficient 0.13), and Vehicle cost (coefficient 0.01).

The model´s R^2 value is 0.99983, which is very close to 1. This indicates that the model demonstrates a high level of accuracy, likely due to the limited size of the dataset and its exclusive focus on cost items.

The significant differences in absolute values, sum of labour cost, and the number of employees working with smart technologies are also reflected in the econometric model. The variable Employees working with smart technology shows the highest coefficient, which is nearly double that of the second-highest coefficient (Number of employees). It shall be noted that the wage costs for employees working with smart technologies are not significantly higher than those of service employees.

The variables that negatively affect labour costs include the Quantity of sorted waste (coefficient -21) and Difference between sales and sorting costs (coefficient -0.19).

Subsequently, statistically significant variables with a probability of 5% or less were selected to calculate the resulting econometric model equation, which has the following form:

*Labour costs = 6688.180 * Number of employees + 1.555133 * Quantity of municipal waste – 20.92232 * Quantity of sorted waste + 0.130746 * Sorting costs + 0.008971 * Vehicle costs + C*

In the resulting econometric model, the variable Number of employees had the largest positive impact on Labour costs (coefficient 6688). Other variables influencing labour costs include Quantity of municipal waste (coefficient 1.56), Sorting cost (coefficient 0.13), and Vehicle cost (coefficient 0.01). Conversely, labour costs are negatively influenced by Quantity of sorted waste (coefficient -21).

4 Discussion

In the circular economy, secondary raw materials are essential for minimising waste and maximising resources utilisation, which, in turn, fosters innovation, creates new business opportunities, and drives economic growth. By using secondary raw materials, the EU reduces its dependence on the import of primary resources necessary for industrial production and mitigates related geopolitical risks. The following section of the paper addresses the formulated research questions.

RQ1: What is the average resale value of selected secondary raw materials within the EU?

This question aims to determine the average resale value of secondary raw materials that support the development of the circular economy and enable cities and companies to better plan and make strategic decisions regarding the optimisation of recycling processes and material reuse in waste management. The analysis shows that in 2021, the most valuable secondary raw material was plastic (400 EUR/t), followed by sorted paper (175 EUR/t), and glass (67 EUR/t). As for glass, it shall be noted that the system of returnable beer bottles has been used for several decades in nearly all EU countries, with a recovery rate exceeding 95%. Bottles are reused 22 times on average within six to seven years before being recycled.

RQ2: How do selected smart technologies affect the costs of waste management in the selected urban centre?

The analysis examines the potential of smart technologies to significantly reduce the cost of waste management by increasing the effectiveness of waste collection and treatment, thereby contributing to the modernization of services and the improvement of waste management in urban centres. The analysis focused on the cost-effectiveness of four categories:

Operation of waste management companies accounts for 41% of the total costs, indicating that nearly 50% of all expenses are related to the operation and management of waste management companies.

Hardware accounts for 35% of the total costs and includes all physical components and equipment necessary for operations.

Software accounts for 14% of the total costs and encompasses all programs and applications used in operation.

Network connectivity is the smallest cost item, representing 10% of the total costs and includes the cost of internet connection and network maintenance.

The results indicate that the most significant financial burden is associated with the operation of waste management companies, while network connectivity is the least costly item.

RQ3: What are the projected financial savings in waste management in the selected urban centre?

Forecasting financial savings allows urban centres to better plan budget and allocate resources more effectively. Predictive models highlight opportunities to optimise and improve processes, aiding decision-making on investments in new technologies and infrastructure, and improving overall performance of waste management. Based on the results presented in this section of the paper, the development of financial savings in waste management for one of the selected urban centres in Slovakia were projected for a period of four quarters, i.e., for the whole year 2022.

Table 2 Forecasting financial savings development

30% savings	40% savings	55% savings
Wage		
decrease by EUR 3.8 million labour costs – decrease by EUR 5.8 million	decrease by EUR 5.1 million labour costs – decrease by EUR 7.7 million	decrease by EUR 7 million labour costs – decrease by EUR 9 million

30% savings	40% savings	55% savings
Number of employees		
decrease by 152 employees	decrease by 203 employees	decrease by 279 employees
Cost of vehicle fleet		
decrease by EUR 4 million	decrease by EUR 8 million	decrease by EUR 7.3 million
Vehicle kilometres travelled		
decrease by 0.7 million km	decrease by 0.615 million km	decrease by 0.46 million km

Source: the authors

Labour costs. The cumulative forecast for the year 2022 is projected to be below EUR 12.8 million. A 30% reduction would lead to savings of EUR 3.8 million, bringing total labour costs down to EUR 9 million. A 40% reduction would decrease costs by EUR 5.1 million, resulting in total labour costs of EUR 7.7 million. The largest reduction, 55%, would yield savings of over EUR 7 million, lowering the total wage bill down to just under EUR 5.8 million.

In the category of labour costs, changes in the minimum wage, which affects Saturday and public holiday allowances (especially for service staff), may lead to wage increases beyond those stipulated in the collective agreement.

Number of employees. In calculating potential staff reductions, figures for service staff have been used, as the implementation of smart technologies is expected to have a greater impact in this category. As the adoption of smart technologies increases, there will be a growing need for administrative staff to manage data, ensure its accuracy, and review routes for collecting bins.

The average number of service staff projected for the year 2022 is 508. With a 30% reduction, the number of staff would decrease by 152 (to 356). A 40% reduction would decrease the number of employees by 203, leaving 305 employees. A 55% reduction would lead to a decrease of 279 employees, bringing the total down to 229. The crew typically consists of one driver and two passengers, so the majority of the reductions would occur among the passengers, with fewer cuts among the drivers.

Cost of vehicle fleet. Fleet size, vehicle body size, motorization, and the energy efficiency of vehicles (mild-hybrids or all-electric vehicles in the future) are important factors in calculating projected and potential vehicle cost savings. The working hours of vehicle align with those of the driver – eight hours per day.

The forecast for 2022 is EUR 13.2 million. A 30% reduction would result in savings of just under EUR 4 million, reducing the total fleet cost to EUR 9.2 million. A 40% reduction would save EUR 5.3 million, bringing the total cost down to just under EUR 8 million. The largest saving (55%) would amount to over EUR 7.3 million, lowering total vehicle fleet costs to just under EUR 6 million.

Vehicle kilometres travelled. The number of kilometres travelled by vehicles is directly related to the efficiency of service routes. The more efficiently the routes are planned, the greater the overall efficiency. Currently, routes are planned according to fixed collection days. The application of smart technologies would introduce a dynamic approach, allowing for daily route planning instead of quarterly scheduling.

The total forecast exceeds 1 million kilometres. A 30% reduction would mean a decrease of 0.3 million kilometres, reducing the total distance to over 0.7 million kilometres. A 40% reduction would result in a decrease of 0.4 million km, bringing the total down to 0.615 million kilometres. The largest reduction, 55%, would lower the distance to less than 0.6 million kilometres, resulting in a total of 0.46 million kilometres.

The observed predictions indicate a positive trend across all variables, highlighting the potential benefits of cost savings in each of the areas analysed. This will have a positive impact on the profitability of the company under review. Smart technologies hold significant potential for reducing costs associated with waste collection, transportation, and treatment. Their implementation can bring substantial savings, improved service quality, and reduced environmental impact. However, the success of these technologies depends on their effective implementation, integration into existing systems, and the resolution of potential challenges.

These findings offer several benefits for *waste management professionals*:

- An overview of data on secondary raw material prices enables cities and companies to better anticipate future trends and prepare for potential market fluctuations, aiding more effective planning and sales of recycled materials.
- Monitoring the level of municipal waste sorting provides crucial insights to help meet legislative requirements, enhance waste management efficiency, improve public image and community engagement, thereby fostering trust and support from

residents and customers and promoting the circular economy.

- The proposed predictive model will allow cities and companies to better plan financial budgets and allocate resources efficiently, thereby reducing the overall financial burden associated with waste management.

For *environmental policymakers,* the study highlights the inconsistent implementation of smart technologies in waste management across various municipalities and the delays in reporting on their deployment. Therefore, policymakers are advised to:

- Develop and implement strategic plans tailored to the specific needs of individual municipalities in implementing smart technologies in waste management.
- Establish and promote uniform standards and regulations for the implementation of smart technology.
- Introduce systems of regular monitoring and evaluation of smart technology efficiency to ensure optimal functionality and identify areas for improvement.
- Create mechanisms for the timely and transparent dissemination of information regarding smart technology implementation, ensuring accessibility for all stakeholders.

For researchers, this study contributes to the growing body of knowledge in the area of waste management, recycling, and the circular economy, especially in the context of the transition from Smart City 3.0 to Smart City 4.0. The findings may inspire the development of new technologies and innovative approaches to enhance waste management practices and boost recycling rates.

Conclusion

Smart technologies play a key role in the implementation of sustainable business practices and support of CSR initiatives by helping cities and companies to achieve environmental and social objectives. Integrating these technologies into business and environmental strategies enables companies and cities to effectively respond to contemporary challenges, optimise resource utilisation, reduce environmental impact, and improve quality of life. The concept of Smart City represents a fundamental shift in urban planning, where technology, data, and innovation are combined to create efficient, sustainable, and liveable cities. While this concept has been successfully implemented in multiple countries for several years, the extent and depth of these solutions vary significantly. Therefore, direct comparisons between cities with the implemented Smart City concept are not feasible; instead, individual elements should be compared. Waste management is currently undergoing significant transformations, particularly in terms of standardisation and legislative uniformity across the European Union.

The research aimed to analyse the impact of smart technology implementation on financial savings in a specific urban centre in Slovakia. This objective was achieved through the proposed econometric model, which enabled the forecasting of financial savings in this centre resulting from the adoption of smart technologies in waste management.

The theoretical section provides an overview of the historical development of the Smart City concept in the context of waste management. The empirical section of the research demonstrated that, by comparing the average resale value of selected secondary materials in the EU, plastic emerged as the most expensive secondary material in the analysed period (400 EUR/t). The high price of plastic can be attributed to its complex processing and the growing demand for recycled plastic, which finds its use across many industries throughout the whole European Union, thereby increasing its economic value.

Further research findings revealed that the largest share of the total costs in waste management is attributed to the operation of waste management companies, accounting for 41%. This high percentage is due to the costs associated with day-to-day management and operations, including labour costs, maintenance costs, and other operational expenditures essential for the effective functioning of these companies. The second-largest cost category is hardware, representing 35% of the total costs, encompassing all physical smart devices necessary for operations, such as smart containers, separation machines, and other technical equipment. This share reflects the high costs of purchasing, maintaining, and modernizing hardware, which is crucial for effective waste treatment and management.

The research also focused on forecasting financial savings in waste management for a selected urban centre at savings levels of 30%, 40%, and 55%. The areas analysed were labour costs, vehicle fleet costs, number of employees, and vehicle kilometres travelled.

This study offers several benefits for researchers, expanding knowledge in the field of waste management within the context of Smart City 4.0. For practitioners in the field of smart city development, the study provides an overview of secondary material prices in the European market, insights into the pricing of municipal waste based on the level of sorting in Slovakia, and the potential for financial savings in waste management using the proposed and tested predictive model. For policymakers, the study advises the implementation of strategic plans that consider the specific needs of various municipalities when adopting smart technologies and the establishment of mechanisms for timely and transparent disclosure of information on the implementation.

The research had several limitations. First, there is a time lag in the public availability of information on the effects of smart technology implementation. Second, the research was not conducted across the entire waste management sector or multiple municipalities; instead, the savings of individual items were analysed in a smaller sample. This is because individual municipalities do not consistently require waste collection companies to implement the smart technologies addressed in this research. Third, there was limited digitization and use of smart technologies in waste management, except in a few cases.

Further research could expand the research sample to include multiple urban centres in Slovakia and other European countries, particularly after the necessary legislation is enacted to encourage companies in waste collection, treatment and disposal to adopt uniform current smart technologies and disclose up-to-date information related to their implementation. Additionally, there should be an obligation to implement automated weighing systems, including the availability of precise pricing for waste collection. This would allow consumers to better understand their waste bin usage and ecological print, thereby encouraging more effective waste sorting and contributing to the recovery of natural capital.

Further research could also focus on marketing communication between waste management companies and the public, with the aim to provide information about new smart solutions and educate and incentivise both the public and the industrial sector to sort waste more effectively and minimise landfill and municipal waste.

Declarations

Availability of data and materials

The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

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