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Integrating Logistics and Information Systems in Urban Waste Management: The Road to a Sustainable Smart City

Gabriel Koman[1] and Silvia Krúpová[1*]

[1]*University of Žilina, Department of management theories, Faculty of management science and informatics, Univerzitná 8215/1, 010 26 Žilina, Slovak republic; Email: silvia.krupova@fri.uniza.sk, gabriel.koman@fri.uniza.sk*

***Corresponding Author:** Silvia Krúpová

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Abstract: The integration of logistics and information systems in urban waste management is a key step towards building sustainable smart cities. In the context of increasing urbanisation and environmental challenges, cities are forced to look for more efficient solutions for waste management. This paper explores how the interconnection of logistics and modern information technology can optimize waste collection, sorting and recycling processes, reduce operational costs and minimize negative environmental impacts. Using smart sensors, monitoring systems and analytical tools, it is possible to improve the planning of waste collection routes and predict the needs of different areas. The result is greater efficiency in urban waste management, leading to reduced landfill waste production and better use of recyclable materials. This article also highlights the need for coordinated cooperation between the public and private sectors, as well as the importance of a legislative framework that promotes technological innovation and environmental sustainability. Integrating these solutions into the infrastructure of modern cities contributes to their transition towards sustainable and smart urban ecosystems.

Keywords: Smart city management, logistics, waste management, information systems, benefits

1. Introduction

The development of modern cities is increasingly dependent on the efficient management of urban services, including waste management. With growing populations, increasing consumption and urbanisation, cities are facing more complex challenges in waste treatment and management. Traditional approaches to waste management are often inefficient and unsustainable, leading to infrastructure congestion, increased costs and negative environmental impacts. In the context of the increasing digitisation of urban processes and smart city initiatives, information systems play a key role. These systems enable real-time data collection and analysis, optimisation of logistics processes and increased efficiency of waste management. The integration of logistics and information technology thus forms the basis for improving waste collection, treatment and recycling processes, thereby contributing to sustainable urban development. The logistics of waste management, which includes waste collection, transport and disposal, can be made significantly more efficient through intelligent systems. Sensors, geolocation tools and traffic management systems enable optimisation of collection vehicle routes, reduce greenhouse gas emissions and minimise operating costs. This integration not only leads to an improvement in the ecological footprint of cities, but also creates conditions for residents with a better quality of life. The aim of this paper is to investigate how the integration of logistics and information systems in waste management contributes to achieving the goals of a sustainable smart city. We will focus on current trends, challenges and practical examples that illustrate how effective waste management can support the development of sustainable cities of the future.

2. Methodology

The information presented in this paper was obtained using data mining, processing and evaluation methods. The document analysis method was applied to collect the data, which focused on obtaining relevant information from technical articles, studies and statistical reports related to waste management and the integration of logistics and information systems. The methods of comparison, deduction and synthesis were used to process the data. Conclusions from the analysis were formulated based on inductive logic. Several criteria guided the selection of the analysed documents. Documents that did not meet these criteria were not included in the analysis. The inclusion criteria were as follows:

- Focus on the integration of logistics and information technology in waste management.
- Studies had to be published after 2015, due to the rapid development in smart city technologies and dynamic changes in waste management.
- The documents had to reflect sustainable solutions in the context of smart cities.

Additional data was collected from secondary sources, mainly from case studies on the implementation of smart solutions in urban waste management. These studies came from smart city technology providers' websites, annual reports and product catalogues. To be included in the analysis, the case studies had to include quantifiable improvements in waste management efficiency and environmental impact. Finally, the formulation of recommendations and conclusions was based on a logical analysis of the results, combined with a creative approach to designing innovative solutions for the urban environment.

3. The Smart City Concept

The concept of "smart city" represents a vision of modern cities that use advanced technologies, especially information and communication technologies (ICT), to increase the efficiency of urban services, improve the quality of life of citizens, promote sustainability and optimise the use of resources. Under this vision, cities are equipped with smart infrastructure that enables the efficient management of various areas of urban life such as transportation, energy, waste management, security, and health [1,2].

A smart city is a city that integrates technological solutions to improve the quality of life of citizens, increase the efficiency of public services, and reduce environmental impacts. These technologies are based on IoT (Internet of Things), big data, sensor networks and cloud computing, which enable the collection, analysis and processing of large amounts of data from urban systems in real time. This results in better monitoring and management of urban services, optimization of resource use and decision support.

The smart city concept focuses on integrating multiple aspects of urban life.

The main components include:

- Smart governance: the use of technology to improve the transparency and efficiency of urban governance, including e-government and online services.
- Smart mobility: Intelligent transport systems that optimise traffic, public transport and reduce emissions through dynamic traffic management and shared mobility solutions such as bicycles and electric scooters.
- Smart environment: reducing a city's ecological footprint through energy efficient solutions, smart waste management and improving air quality.
- Smart living: Improving the quality of life in housing, healthcare, education and security through technologies that enable monitoring and optimization of conditions in urban neighbourhoods.
- Smart economy: Promoting innovation, digital technologies and entrepreneurship in cities to increase competitiveness and economic growth.

One of the most important smart city technologies is the Internet of Things (IoT), which connects different sensors and devices, allowing them to communicate and share data in real time [3]. These sensors can monitor traffic, energy consumption, the condition of public facilities and the environment. With this data, city authorities can respond to problems in real time, prevent problems and improve the efficiency of service delivery [4].

The smart city concept emphasizes environmental sustainability, which includes reducing energy consumption, using renewable resources, and minimizing emissions. Cities are responsible for a significant portion of global CO_2 emissions, and therefore it is important to reduce their carbon footprint through intelligent management of energy resources, such as smart grids that optimize energy consumption in homes and businesses.

Smart cities also apply advanced solutions in the field of waste management. Using smart sensors that monitor the fullness of waste bins, cities can plan waste collection more efficiently, reduce costs and minimise environmental impacts environment. This approach also promotes higher recycling rates and reduces the amount of waste going to landfills [4-6].

Citizens play an active role in smart cities. Technology enables citizens to better interact with city services, participate in city governance and provide feedback. Apps and platforms allow residents to report issues such as potholes, waste problems or traffic obstructions, contributing to faster resolution of these problems.

4. The Role of Logistics in Smart City Waste Management Supported by Information Systems

In the smart city concept, waste management logistics play a key role in improving the quality of life of citizens and ensuring the sustainability of urban processes. Logistics in waste management encompasses all activities related to the collection, sorting, transport, treatment and disposal of waste, and the use of advanced information systems allows these processes to be optimised and their environmental impact reduced. As the urban population grows and the volume of waste produced increases, effective logistics management is becoming increasingly important, especially in the context of sustainability efforts.

One of the main benefits of logistics in smart city waste management is the optimization of waste collection. Information systems supporting logistics operations, such as Internet of Things (IoT)-based systems, use sensors to monitor the fullness of waste bins in real time. Based on this data, collection vehicle routes can be optimized, leading to reductions in fuel consumption, CO_2 emissions and operational costs [5,7]. Optimized routes also reduce traffic congestion and the time required for waste collection, thus increasing the efficiency of the whole process.

Another important benefit of waste management logistics in smart cities is the use of automated systems for waste sorting and recycling. Logistics processes supported by information systems can efficiently sort waste based on its composition, thereby increasing recycling rates and reducing the volume of waste going to landfills [8]. These systems use artificial intelligence and machine learning to recognise and sort waste, reducing the need for manual labour and increasing recycling accuracy [9]. Information systems integrated into the logistics processes of waste management enable continuous monitoring of process quality and real-time performance evaluation. Managers can track container fill rates, collection and recycling efficiency, and potential system failures or errors [10]. These systems provide important data that can then be analyzed to optimize processes, predict future needs, and develop effective waste management strategies [11]. Information systems used in waste management logistics provide managers with decision support tools. By analyzing data collected during waste collection, transportation, and processing, managers can make informed decisions regarding improving the efficiency of logistics processes, infrastructure investments, and capacity planning based on long-term trends [1]. Predictive models allow cities to better respond to changing conditions, such as seasonal fluctuations in waste production or increasing demands due to increasing urbanization [12]. Logistics in waste management, supported by information systems, contributes to the environmental goals of smart cities. Effective management of waste collection and sorting helps to reduce the production of landfilled waste, minimizing the negative impact on the environment. Improved recycling processes and reduced CO_2 emissions due to optimised logistics processes also contribute to the achievement of the Sustainable Development Goals [13,14].

The integration of IoT and big data into waste management logistics processes enables the acquisition of large amounts of data in real time. This data is then analysed and processed to improve system performance and optimise decision-making processes. This enables the city to better anticipate waste collection needs, identify patterns in residents' behaviour and respond to waste management challenges.

5. Case Studies

The previous chapter analysed the key role of logistics in waste management in smart cities, showing how information systems, IoT, big data and artificial intelligence, enable more efficient planning, route optimisation, waste prediction and improvement of recycling processes.

These technologies bring significant benefits for sustainability and efficiency in urban waste management. To support this theoretical knowledge with real examples, the following case studies will demonstrate how linking advanced logistics systems with modern technologies can transform waste management and contribute to the sustainable development of smart cities, see table 1.

Table 1 Criteria for selected case studies. Source: authors

Criterion	Description
Technological innovativeness	Advanced technologies such as IoT, big data, AI, cloud computing to optimise waste management.
Sustainability and environmental benefits	Reduce emissions, optimise logistics and improve recycling.
Scalability of solutions	Solutions applicable in different cities and regions.
Successful implementations and results	Measurable improvements - lower costs, higher recycling rates, reduced waste.
Geographical and cultural diversity	Representation of cities from different world regions.
Promoting a circular economy	Cities involved in circular economy initiatives - waste minimization.
Smart City initiatives	Cities part of wider smart city strategies and infrastructures.

The following criteria were set for the selection of the case studies:

Technological innovativeness

- Each of the selected cities had to be a pioneer in adopting advanced technologies such as IoT sensors, big data analytics, predictive analytics, artificial intelligence or cloud computing. These technologies were key to effective waste management and optimising collection routes.

Sustainability and environmental benefits

- The selected cities had to demonstrate that their waste management systems have contributed to reducing the environmental burden, in particular by reducing CO_2 emissions, reducing energy consumption and improving recycling processes. The ability of cities to optimise logistics was also an important factor, minimising the negative impact on urban transport and improving air quality.

Scalability of solutions

- The technologies used in these cities had to be scalable and transferable to other cities around the world. The case studies were intended to show that these solutions are not only applicable in the local context, but can serve as a model for other smart cities to build their own waste management systems.

Successful implementations and results

- The selected cities had to have measurable results in terms of improved waste management efficiency. These included cost reductions, increased recycling rates, more efficient use of resources, all backed up by concrete data and research. Results had to be published after 2018 to reflect the current state of the technology and its impact on smart cities.

Geographic and cultural diversity

- Geographical diversity was also taken into account when selecting the cities to ensure that different parts of the world were represented - Europe (Barcelona and Amsterdam), Asia (Seoul) and the Middle East (Dubai). This diversity has ensured that waste management solutions are not tied to one region, but are relevant and adaptable to different geographical and cultural conditions.

Promoting a circular economy

- An important criterion was the approach to circular economy, i.e. the ability of cities to use waste materials as resources and minimise waste in landfills. Cities such as Amsterdam are heavily involved in initiatives that promote sustainable and circular materials management, which was key to their selection.

Smart City initiatives

- The selected cities had to be part of larger smart city initiatives, with the technologies used to manage waste being integrated into the wider smart infrastructure. Such cities have demonstrated that waste management is part of a comprehensive vision for a smart and sustainable future, as seen for example in Dubai and its Smart Dubai programme.

Based on the information gathered and the analysis, four cities (Barcelona, Seoul, Amsterdam, Dubai) were selected to best represent the different aspects and approaches to waste management in the context of smart cities. These criteria ensured that the selected cities represent innovative, efficient and sustainable approaches to waste management that can serve as an example for other metropolises on the path to smart cities. The case studies show the different approaches to waste management in smart cities and the importance of information systems in optimising these processes.

5.1 Case Study – Smart Waste Management in Barcelona, Spain

Description: Barcelona, one of the leading smart cities in Europe, implemented an advanced waste management system based on IoT and data analytics. The city has equipped containers with sensors that monitor their fullness in real time. Using this technology, the city can optimize waste collection routes and minimize transport costs, while reducing CO_2 emissions [5].

Technological support: Using technology from Urbiotica and the city's data centre, it was possible to manage and analyse data in real time, improving the transparency and efficiency of the system. In addition, prediction algorithms helped to identify seasonal changes in waste production and adjust collection frequency accordingly [14].

Results: The project led to a 20% reduction in the number of collection vehicle trips, which resulted in significant reductions in fuel consumption and emissions. The system also allowed for better planning and a reduction in the overall operational costs of waste collection [5].

5.2 Case Study – Automated Waste Collection in Seoul, South Korea

Description: A smart waste management project is being implemented in Seoul, where underground piping systems are used for waste collection. This system replaces traditional containers and collection vehicles. Residents drop their waste into special stations, from where it is piped to central recycling facilities. This system uses advanced sensors and controllers to monitor waste transport in real time [15].

Technological support: information systems support this process with control units that monitor waste flow, optimize the route in the pipeline and prevent congestion. The system is fully automated, which reduces the need for manpower and limits human error [16].

Results: The need for traditional collection trucks was reduced by 80%, minimizing congestion and emissions. Automation has also enabled city authorities to achieve better recycling results, as waste is already sorted when it enters the system [16].

5.3 Case Study – Smart Waste Management in Amsterdam, Netherlands

Description: Amsterdam is known for its integrated approach to smart city, and one of the key initiatives is smart waste management. Sensors installed in waste containers monitor fill levels and inform city systems when containers need to be emptied. The data is analysed to predict optimal routes for collection vehicles [17].

Technological support: The city works with the City Data platform and EcoTech to provide big data analysis and predictive analytics. In this way, city authorities can predict trends in waste production and plan operational capacity [17].

Results: Optimized waste collection routes reduced operational costs by 15% and emissions by 18%. At the same time, transparency of the process has increased, and city staff have better insight into where and when capacity issues arise [18].

5.4 Case Study – Innovative Waste Collection System in Dubai, United Arab Emirates

Description: Dubai, one of the fastest growing smart cities, implemented an innovative waste collection system using IoT sensors and smart software to manage waste collection. The systems monitor container fullness in real time and use artificial intelligence to plan optimal collection vehicle routes [19].

Technology support: Cloud computing and AI-based information systems integrate data from multiple sources, including sensors and historical data, enabling dynamic planning and prediction of future needs. This system is part of the broader Smart Dubai initiative [19].

Results: The system has reduced operational costs of waste collection by 25% and achieved better recycling performance. The system has also contributed to a reduction in greenhouse gas emissions due to optimised transport and more efficient use of resources [20].

The following table 2 defines the technologies used within each city for smart waste management, where IoT sensors, data analytics, predictive models and automated systems play a key role.

Table 2 Criteria for selected case studies. Source: authors

Case study	Technology
Barcelona, Spain	• IoT sensors to monitor container fullness • IoT sensors to monitor the fullness of containers • Algorithms to predict waste production and optimise routes • Urban data centre
Seoul, South Korea	• Underground pipeline system for waste transportation • IoT sensors and controllers to monitor waste transportation • Automated waste sorting and transportation system
Amsterdam, Netherlands	• IoT sensors for container fullness monitoring • Big data and predictive analytics for route planning • City Data platform for data integration and analytics • Software for dynamic management of collection vehicle routes
Dubai, United Arab Emirates	• IoT sensors for real-time container monitoring • Cloud computing for data processing • Artificial intelligence to predict waste collection needs and optimize routes • Smart software for route planning

6. Benefits for Smart Cities Management

In the context of urban development, smart cities represent a pivotal approach to enhancing residents' quality of life while addressing challenges such as population growth and sustainability. Effective management of smart city initiatives is underpinned by theoretical knowledge and insights from case studies. Theoretical frameworks provide essential models for decision-making, while case studies offer empirical evidence of best practices and lessons learned. This synthesis of theory and practice equips urban planners and policymakers with the necessary tools to design, implement, and evaluate smart city strategies. Analyzing the benefits of this integration highlights its role in fostering informed decision-making, innovation, and stakeholder engagement, ultimately contributing to the creation of resilient urban environments.

- Optimizing waste collection: Thanks to IoT sensors that monitor the fullness of waste bins, cities can efficiently optimize waste collection routes. This leads to fuel savings, reduced CO_2 emissions and better use of labour.
- Cost reduction: information systems enable prediction and automation of waste collection, which reduces operational costs associated with waste collection and recycling, including reduced maintenance and fuel expenses.
- Improved control and monitoring: digitalization of waste management provides cities with a continuous overview of the state of their infrastructure and enables real-time and timely problem solving.

- Promoting sustainability: the use of information systems enables cities to improve recycling, reduce waste production and minimize the volume of waste going to landfills, thereby increasing environmental sustainability.
- Improving the quality of life of residents: effective waste management leads to cleaner public spaces, contributing to improved sanitation and overall quality of life in cities.
- Predictive maintenance and planning: thanks to big data and analytical tools, cities can predict and plan infrastructure maintenance, reducing unplanned outages and repair costs.
- Promoting a circular economy: cities use information systems to better sort and recycle waste, thereby promoting a circular economy and reducing material waste.

These benefits for smart cities and city management are supported by relevant case studies and resources that show how effective integration of information systems and logistics solutions brings improvements in waste management and supports the sustainability of urban areas. Possible Challenges and opportunities for smart cities management arising from theoretical knowledge and case study analysis:

- Technological infrastructure: Ensuring a robust technology infrastructure is a key challenge as successful implementation of information systems and IoT devices in waste management requires a stable network, coverage and maintenance of technologies.
- High initial investment: Deploying smart technologies in waste management logistics, including sensors, software and data platforms, requires significant financial investment, which can be costly for many cities.
- Data security and privacy: With the increasing use of IoT devices and data platforms, the risk of cyber-attacks increases. Managing and protecting sensitive citizen data and infrastructure thus becomes a key challenge.
- Integration of different systems: Cities often face challenges in integrating different information systems and technologies that are used in different management sectors, which can lead to delays and complications.
- Public acceptance and education: The success of implementing smart technologies in waste management also depends on public acceptance and cooperation of residents. Educating citizens about the benefits of these technologies is essential.

Given the complexities and limitations of integrating logistics and information systems in urban waste management, it is crucial for managers to strategically plan the development of an ICT framework. They must assess competitive use cases and prepare for potential challenges.

7. Conclusion

The analysis of case studies from different cities has shown that the implementation of smart waste management systems leads to optimized collection, reduced costs and improved environmental sustainability. Case studies such as initiatives in cities like Barcelona, Copenhagen and Singapore illustrate how technologies such as IoT sensors and analytics tools are enabling cities to improve monitoring and management of waste management. In Copenhagen, for example, smart waste bins have been implemented and have helped to optimise collection routes, reducing emissions and operational costs. Barcelona is using data to improve waste sorting and more efficient collection planning, leading to higher recycling rates. Case studies show that cities investing in innovative technologies and information systems can enhance both their environmental profile and citizens' quality of life. Effective waste management contributes to the circular economy and supports urban economic development. In conclusion, implementing logistics and information systems in waste management is key to building sustainable smart cities. To achieve this, cities must overcome challenges like technological investment and public acceptance while leveraging the benefits of modern technologies.

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