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Driving the Circular Economy in E-Commerce: AI and Green Information Systems for Transforming Parcel Lockers into Reverse Logistics Hubs

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Abstract: This article examines the issue of mitigating the negative environmental impact of the e-commerce sector through the implementation of green information systems (Green IS). The main research objective of the article is to assess the potential of parcel lockers as active reverse logistics hubs, enabling circular packaging management within the so-called 'last mile'. The empirical study was carried out in 2024 using the CAWI method on a nationwide sample of 1,080 adult internet users. The results showed widespread use of parcel lockers (91.6%) and a high willingness among consumers to return packaging (80%), alongside a critical assessment of the environmental sustainability of current packaging standards. The data obtained were used to design a proprietary, multi-layered architecture for the Green IS (Circular APM Ecosystem) system, based on deep learning models (LSTM). This integration enables the optimisation of courier routes and parcel locker capacity, leading to a reduction in the carbon footprint and the implementation of an efficient circular economy.

Keywords: Postal Infrastructure, Circular Economy, Green Information Systems, Artificial Intelligence (AI)

Introduction

The rapid growth of the e-commerce sector over the last two decades has become one of the main drivers of the modern economy; however, this growth exacerbates serious challenges in the area of sustainable development (Rolando & Mulyono, 2025; Hu et al., 2025; Rolando et al., 2025).

The first of these challenges is the high complexity of logistics processes at the so-called 'last mile' stage. This is the most environmentally and financially burdensome element of the supply chain; consequently, postal operators are seeking cost-effective and environmentally friendly alternatives to traditional door-to-door deliveries. One such solution is the expansion of off-premises collection point infrastructure, with a particular focus on parcel lockers. These solutions not only reduce the risk of failed delivery attempts and allow for flexible collection of parcels around the clock, but are also evolving into multi-functional hubs handling dispatches, returns and click-and-collect services (Encarnación & Amaya, 2025; Ozyavas et al., 2025; Zhang & Demir, 2025). Poland is the European leader in implementing such solutions – as indicated by the empirical research from 2024 presented in this paper, the use of parcel lockers has become widespread in the country and is reported by 91.6 per cent of adult internet users.

The second major challenge is environmental pressure resulting from the generation of massive amounts of packaging waste in e-commerce (Clement & Spinler, 2025; Ram et al., 2025). Research findings indicate a high level of consumer dissatisfaction with current parcel packaging methods – over one-third of respondents rate the environmental friendliness of current packaging negatively, with particular focus on cushioning materials (37% of negative ratings). There is clearly a significant discrepancy between growing public expectations regarding environmental protection and the operational practices of the e-commerce market. However, it should be noted that the widespread availability of parcel locker infrastructure offers the potential to resolve this issue by transforming these lockers into active reverse logistics points for reusable packaging. This solution is supported by 80% of the users surveyed. However, the tool enabling this transformation is Green Information Systems (Green IS), defined as advanced digital solutions supporting sustainable operational and environmental processes. In the context of the Smart Cities concept, Green IS are becoming a key tool for supporting the achievement of the UN Sustainable Development Goals (in particular Goal 12: Responsible Consumption and Production, and Goal 13: Climate Action) through intelligent resource management and the reduction of the carbon footprint. Real-time data analysis and event prediction play a key role here; in the relevant literature, these are based, amongst other things, on Gaussian process models, state space models and deep learning algorithms.

Despite the growing number of publications focusing on optimising 'last-mile' deliveries and the applications of artificial intelligence in logistics, there remains a noticeable research gap in the existing literature regarding the integration of the behaviouralwith the Green IS technological architecture in the context of the circular economy. Existing studies describe parcel vending machines as static or one-way parcel distribution points, overlooking their potential as dynamic two-way nodes (Ammara et al., 2022; Brinken et al., 2023; Budziewicz-Guźlecka & Drab-Kurowska, 2021; Burlacu et al., 2022; Huda et al., 2024). There are also few studies combining empirical verification of consumer declarations regarding the return of reusable packaging with advanced predictive analytics (e.g. LSTM models) within a dedicated, multi-layered system architecture.

The main objective of this article is to address this gap by assessing the potential of parcel vending machines as active nodes in reverse logistics within a circular economy model, and by designing a proprietary, multi-layered Green IS system architecture (Circular APM Ecosystem). To achieve this research objective, the following main research question was posed: How can the Green IS system architecture, utilising parcel vending machines and deep learning models (LSTM), help mitigate the negative environmental impact of e-commerce logistics through the development of a circular economy in the 'last mile'?

To clarify this problem, three specific research questions were formulated in the areas of consumer behaviour, technology and the environment.

Consumer dimension: What is the readiness and attitude of e-commerce consumers towards the use of parcel lockers as active return logistics hubs for reusable packaging?

Technological dimension: How can consumer behaviour data be linked to deep learning algorithms (LSTM) within the multi-layered Green IS architecture to optimise the capacity of parcel lockers and courier routes?

Environmental dimension: To what extent does the implementation of the Circular APM Ecosystem concept enable a reduction in the carbon footprint and the closure of the material cycle in last-mile logistics processes?

Literature review

As noted earlier, the rapid growth of the e-commerce sector is shaping modern distribution processes, in which the 'last mile' stage plays a key role (Rolando & Mulyono, 2025; Hu et al., 2025; Rolando et al., 2025).

In an effort to optimise operating costs and reduce the carbon footprint of deliveries, logistics operators are rolling out parcel locker infrastructure on a large scale (Saber et al., 2025; Stolfi et al., 2025; Zhang & Demir, 2025). This infrastructure streamlines the delivery process, prevents failed delivery attempts and provides a stable foundation for urban logistics (Encarnación & Amaya, 2025; Ozyavas et al., 2025).

As the volume of parcels increases, so too does the amount of packaging waste generated (Clement & Spinler, 2025; Ram et al., 2025). The implementation of Circular Economy principles requires redefining the role of parcel lockers – from their current function as passive collection points to active reverse logistics hubs. Return logistics at the last-mile stage enables the recovery, reuse and recycling of packaging at the point of delivery (Letunovska et al., 2023; Yan et al., 2024). The effectiveness of such a circular model relies on the acceptance and direct involvement of consumers, whose attitudes determine the extent of utilisation and efficiency of the entire system.

Furthermore, the environmental pressure exerted by e-commerce is driving the evolution of traditional IT towards Green Information Systems (Green IS), which support sustainable business practices (Böttcher et al., 2024; Mat Nawi et al., 2025). They form the digital foundation of smart *cities*, contributing to the Sustainable Development Goals (SDG 12 and SDG 13) (Sewenet & Pisano, 2023).

Through real-time analytics, Green IS optimises transport routes and reduces the carbon footprint (Sewenet & Pisano, 2023). In the literature, traffic prediction encompasses models based on features (Li et al., 2018), Gaussian processes (Salinas et al., 2019), state spaces (Duan et al., 2018) and deep learning (Yin et al., 2021). Of particular importance for multidimensional time series are *Long Short-Term Memory* (LSTM) networks (Balderas et al., 2024), which take into account historical patterns, seasonality and exogenous factors (e.g. weather) (Balderas et al., 2024; López-Blanco et al., 2022). In reverse logistics, LSTM algorithms in Green IS systems enable a shift towards proactive management by predicting the demand for physical and 'virtual' locker capacity.

Previous research into reverse logistics, IT architecture and AI has mainly been conducted in isolation, focusing separately on the vehicle routing problem (VRP) (Chen & Hu, 2024; Yan et al., 2024), tracking technologies (RFID/QR) (Cunha & Mazieri, 2024; Zghair & Konathala, 2025), gamification (Dalgren & Tran, 2025; Shahzad et al., 2023) and AI-based traffic prediction (Yin et al., 2021; Balderas et al., 2024). Table 1 presents a summary of the research gap and a comparison of the traditional approach with the *Circular APM Ecosystem* concept.

Table 1. Comparison of existing approaches in the literature with the proposed Circular APM Ecosystem concept

Dimension of analysis	Existing approaches in the literature	Proposed solution (Circular APM Ecosystem)
Function of parcel machines	Unidirectional, passive collection/drop-off points in a linear model (Encarnación & Amaya, 2025; Zhang & Demir, 2025)	Two-way, active reverse logistics hubs
Prediction and modelling (AI)	Traditional forecasting of parcel traffic and dispatches without taking returns into account (Duan et al., 2018; Li et al., 2018)	Proactive prediction of packaging returns (LSTM) taking exogenous factors into account
The role of the consumer and behavioural science	A study of declared environmental attitudes unrelated to IT architecture (Ram et al., 2025)	Integration of survey data with gamification modules and a loyalty scheme
System integration (Green IS)	Fragmented solutions (separately: VRP, RFID or surveys) (Cunha & Mazieri, 2024; Yan et al., 2024)	A multi-layered, holistic Green IS architecture combining operational data, AI and customers

Source: Authors' own work based on a review of the literature

There is a clear research and design gap in the literature: there is a lack of studies translating empirical insights into consumer attitudes into the operational architecture of Green IS and AI algorithms. This article fills this gap using the *Design Science Research* (DSR) methodology, proposing a *Circular APM Ecosystem* architecture that integrates user behavioural data with a multi-layered Green IS system supported by LSTM prediction.

Research methods

The study was conducted using the quantitative CAWI method on a representative sample of N=1,080 adult Poles, utilising a certified research panel as part of the 'Regional Excellence Initiative' (RID) project. The study formed the basis for the development of an AI-based Green IS architecture for packaging, aimed at sustainable packaging management. The research sample was selected using two-stage stratified sampling. The study population consisted of people aged 18 or over, living in Poland. A total of 1,080 interviews were conducted. The quantitative method and sample selection used in the study allow the results to be generalised to the entire adult population with a margin of error of +/- 3.0% (95% confidence level).

Survey results

The survey revealed that a key issue remains the low assessment of the environmental friendliness of the packaging used; over one-third of respondents rated this aspect negatively (Figure 1). This is particularly evident in the area of filling materials, which were rated negatively by 37 per cent of respondents (Figure 2).

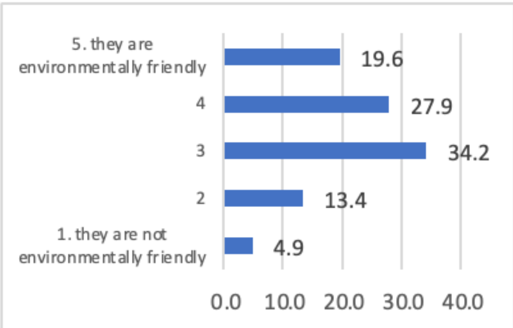

Figure 1. Assessment of the environmental performance of packaging.

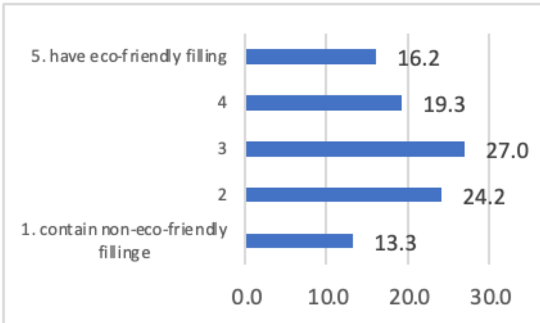

Figure 2. Assessment of the environmental performance of fillings.

The survey also revealed that packaging from ordered products is suitable for reuse (Figure 3). Nearly 40 per cent of respondents indicated that it is often suitable for reuse, whilst 31 per cent felt it was sometimes suitable. For 11 per cent of respondents, it is always suitable for reuse. It should also be emphasised that the majority of respondents would be interested in the option of leaving parcel packaging in a parcel locker immediately, so that it can be reused – nearly one in three respondents would be very interested in this solution, whilst one in two would be somewhat interested (Figure 4).

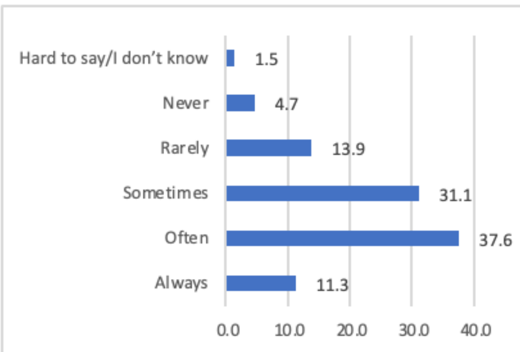

Figure 3. The possibility of reusing packaging from ordered products.

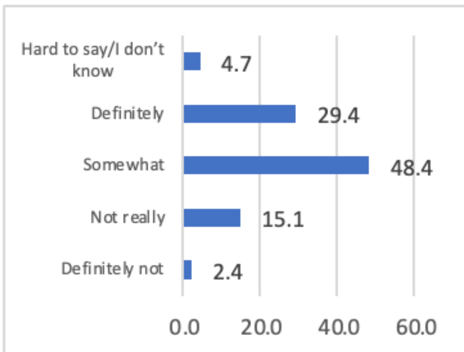

Figure 4. Interest in the option of leaving parcel packaging in the parcel locker immediately.

This is an important signal for parcel locker operators to implement such a service as soon as possible. It also demonstrates the public's high level of environmental awareness.

Implementation of the Green IS architecture for packaging

Research indicates a need to implement digital systems for managing the 'last-mile' packaging cycle. The Green IS architecture forms the technological foundation for reverse logistics (Letunovska et al., 2023; Nimmagadda et al., 2025), enabling waste reduction and the decarbonisation of processes through six key operational mechanisms:

- Dynamic Routing: Algorithmic combination of deliveries with packaging returns within a single courier journey, eliminating the need for dedicated transport (Chen & Hu, 2024; Yan et al., 2024).
- Locker Capacity Allocation: Predictive booking of lockers for empty packaging based on local demand forecasts.
- Smart Packaging Tracking: Verification of packaging wear and tear using QR/RFID/NFC technology and its automatic routing for recycling once the cycle limit has been exceeded (Cunha & Mazieri, 2024; Zghair & Konathala, 2025).
- Circular awareness (Ecology Awareness): Providing customers with the packaging's lifecycle history via the app, thereby fostering engagement with the circular economy model.
- Gamification and Incentives: Loyalty schemes that reward users with discounts and points for returning undamaged packaging (Dalgren & Tran, 2025; Shahzad et al., 2023).
- Resource Availability: Real-time monitoring of the availability of reusable packaging ready for reuse at a given hub.

Enabling the practical implementation of the circular economy concept in the field of e-commerce required the creation of a dedicated architecture for circular supply chains. The **Circular APM Ecosystem** is the solution to this need – a high-level Green IS architecture that integrates time series prediction modules (LSTM networks) with dynamic management of parcel locker resources. This integration enables the parallel processing of operational data streams and environmental indicators, transforming traditional delivery infrastructure into a responsible packaging recovery ecosystem (Figure 5).

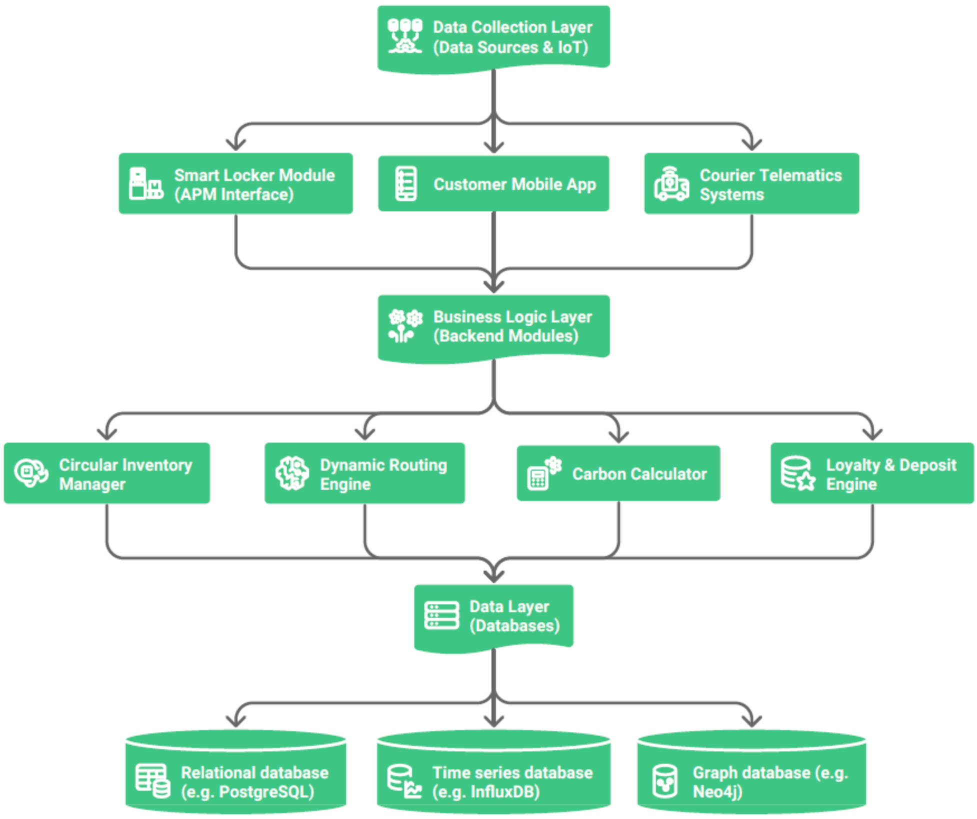

Figure 5. High-level architecture – Circular LPM Ecosystem

Proactive return logistics management within the *Circular APM Ecosystem* architecture is based on three pillars of artificial intelligence analytics:

1. LSTM-based time-series forecasting: The use of LSTM deep learning networks (Balderas et al., 2024; López-Blanco et al., 2022) makes it possible to go beyond simple historical patterns. These algorithms identify the micro-location-specific characteristics of devices (e.g. evening load patterns in residential areas versus peaks in demand in business districts) and the cyclical nature of volume peaks (e.g. sales promotions).
2. Exogenous Variable Analytics: The AI module continuously calibrates forecasts based on external variables. The system analyses weather conditions (which can cause delays in collections) and the dynamics of online retailers' marketing campaigns, dynamically reserving a buffer of lockers for packaging returns.
3. Virtual Capacity Management (Dynamic Capacity Coordination): An advanced traffic control mechanism that influences user behaviour in real time. The system enables predictive allocation of space for returns and suggests alternative nearby APM hub locations in exchange for financial or environmental incentives, thereby preventing infrastructure overload.

Discussion

The results confirm that transforming parcel lockers into active reverse logistics nodes represents an effective approach to decarbonising the 'last mile' and operationalising the Circular Economy in the e-commerce sector.

In response to the first specific research question concerning the consumer dimension, the empirical study revealed widespread use of parcel lockers (91.6%) alongside a high level of consumer willingness to return reusable packaging (80%). A critical assessment of current packaging standards (over 33% negative ratings) indicates market maturity on the demand side, demonstrating that the success of reverse logistics is not limited by a lack of public acceptance, but rather by a shortage of appropriate infrastructure and incentive systems integrated within the proposed ecosystem.

In the context of the second research question, relating to the technological dimension, the combination of behavioural data with AI-driven predictive analytics resolves the key problem of balancing the capacity of OOH machines. The use of LSTM models enables a shift from reactive to proactive management, where taking into account exogenous variables such as seasonality, weather conditions or dynamic promotional campaigns, enables the precise allocation of the 'virtual capacity' of collection points for resource recovery, preventing them from becoming overfilled and optimising courier routes within a single journey.

With regard to the third research question, which focuses on the environmental dimension, the implementation of the Circular APM Ecosystem architecture eliminates the need to create dedicated, separate waste collection chains. Consolidating delivery and return processes at a single point significantly reduces the number of kilometres travelled by courier fleets, which directly translates into a reduction in CO_2 emissions per parcel, whilst extending the life cycle of packaging and increasing the material recovery rate reduces the volume of waste entering the municipal waste stream.

The large-scale implementation of the proposed *Circular APM Ecosystem* architecture faces a number of technological and infrastructural challenges. A significant technical barrier is the requirement for full integration of the IT systems of numerous independent logistics operators, e-commerce platforms, and packaging manufacturers, which necessitates the development of one-way data exchange standards. Another difficulty lies in ensuring the effectiveness of LSTM forecasting models in situations involving sudden, radical market anomalies and in developing a smoothly functioning system for automatically verifying the degree of packaging wear and tear directly at the point of pickup.

Regulatory and legal issues are also important, as they may slow down the scaling of the solution. A key challenge is clearly defining legal liability for damage to or contamination of reusable packaging during transport and storage in package lockers. It is also essential to comply with mandatory sanitary, epidemiological, and quality standards regarding the reintroduction of packaging into circulation. Ensuring full compliance with personal data protection regulations when tracking users' purchasing habits and locations in real time is also crucial.

Last but not least, behavioral and social barriers on the part of customers and market partners pose a significant challenge. Despite initial statements from users indicating a high level of environmental awareness, there is a risk that their engagement will decline over the long term (due to fatigue with gamification mechanisms). Implementing the system requires changing existing shopping habits and convincing customers that immediately returning packaging to a machine does not reduce the convenience of using e-commerce services. On the other hand, online retailers may resist the higher initial costs of implementation and adapting their own packaging processes to the requirements of a circular economy.

A synthesis of these findings provides a direct answer to the main research question: the multi-layered architecture of Green IS, which integrates LSTM models with APM infrastructure, effectively mitigates the environmental impacts of e-commerce, as by combining social potential with proactive technological management, it transforms passive delivery points into a circular logistics network, achieving measurable environmental benefits and closing the material cycle at the last-mile stage.

Limitations and future research

Despite its significant scientific and practical contributions, this study has certain limitations that should be taken into account when interpreting the results. First and foremost, the empirical study was conducted exclusively on a sample of Polish consumers. Although Poland is the leader in the parcel vending machine market in Europe, the specific nature of consumer behavior and local infrastructure may differ from conditions in other countries. Furthermore, the CAWI method used relies on respondents' statements regarding their willingness to return packaging, which creates the risk of a so-called *attitude-behavior gap*—a discrepancy between declared environmental intentions and actual decisions in everyday life. Furthermore, the proposed architecture of the *Circular APM Ecosystem* and the LSTM forecasting models are conceptual and theoretical in nature in this study, meaning they have not yet been tested in the production environment of a major logistics operator.

These limitations point to promising directions for future scientific research. An important next step will be to conduct implementation pilots and simulations under real-world conditions to verify the accuracy of LSTM network forecasts during extreme system loads and parcel peaks. A comprehensive analysis of economic viability also remains an important area of research. Future analyses should estimate capital expenditures and operating costs in the context of e-commerce operators, taking into account the processes of cleaning, inspection, repair, and redistribution of reusable packaging.

Another important direction for research development is the expansion of empirical analyses to include international comparative studies. Validating the model in other European and global markets will allow for an assessment of the universality of the *Circular APM Ecosystem* architecture under different infrastructural, cultural, and legal conditions. This will enable better adaptation of incentive mechanisms and Green IS technologies to the specific characteristics of local supply chains.

Conclusion

This article presents a systemic approach to mitigating the negative environmental impact of the e-commerce sector through the operationalisation of the Circular Economy at the 'last mile' stage.

An empirical study carried out in 2024 on a representative sample of 1,080 Polish internet users revealed a high level of maturity on the demand side – the widespread use of parcel lockers (91.6%) is accompanied by a high level of declared willingness among consumers to actively participate in the return of reusable packaging (80%). These results, combined with a critical assessment of current environmental standards for parcel packaging, justify the need to transform the existing distribution infrastructure.

The main scientific and practical contribution of this work is the proprietary, multi-layered architecture of Green Information Systems – *the Circular APM Ecosystem*. The designed solution integrates consumer behavioural data with artificial intelligence modules, including, in particular, deep learning algorithms based on LSTM networks. The use of time-series analytics and exogenous variables enables precise, proactive forecasting of parcel locker capacity demand and dynamic optimisation of courier routes. As a result, the system transforms passive collection points into active, two-way circular hubs.

The implementation of the *Circular APM Ecosystem* concept leads to significant environmental and operational benefits: consolidating delivery and return processes at a single point reduces courier fleet mileage, lowering CO_2 emissions per parcel and reducing the volume of packaging waste sent to landfill. The results presented demonstrate that combining social capital with technologically advanced Green IS solutions constitutes an effective model for the decarbonisation of urban logistics and provides tangible support for the achievement of the UN Sustainable Development Goals (SDG 12 and SDG 13).

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