SCIENTIFIC OASIS

Management Science Advances

Journal homepage: www.msa-journal.org
eISSN: 3042-2205

Enhancing the Sustainability of Parcel Delivery Systems through Packaging Management and Optimization

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ARTICLE INFO

Article history:
Received 11 November 2025
Received in revised form 10 March 2026
Accepted 21 March 2026
Available online 23 March 2026

Keywords:
Sustainability of the Postal Systems; Optimized Packaging Solutions; Packaging Management; Recyclable Packaging; Reusable Packaging; Real-Size Packaging

ABSTRACT

The introduction of various sustainable packaging solutions and packaging optimization into parcel delivery systems represents a very important step toward improving the sustainability of the entire system. Owing to such an approach and the implementation of different solutions, it is possible to better plan resources, achieve economic savings, and contribute to environmental protection, which all indirectly have a positive impact on society as a whole. This paper aims to highlight the importance of sustainable approaches and solutions for packaging postal items, considering that there is a direct connection between this process and the sustainability of the entire parcel delivery system. This research provides an overview of the contribution to sustainability improvement for three selected approaches: recyclable packaging, reusable packaging, and precisely dimensioned packaging. In addition, through an illustrative numerical example, a significant potential for improving the sustainability of parcel delivery systems through the application of optimized packaging solutions is demonstrated.

1. Introduction

Parcel delivery systems represent key entities within the service sector, as they provide various types of postal and logistics services to a wide range of business and private users. Service providers strive to simultaneously meet user requirements and achieve the highest possible level of profitability [1]. The technological process of parcel delivery comprises several successive phases, among which the delivery phase within the final handover is one of the most technologically and financially demanding [2]. Well-organized delivery is one of the most important segments in the parcel transfer process, also because it represents the phase that involves direct contact with users. In order to optimize delivery, postal operators resort to various solutions [3]. One of the proposed solutions is the provision of services with improved time availability. In addition, the introduction of self-service machines available to users 24 hours a day, seven days a week, is increasingly present in

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https://doi.org/10.31181/msa31202642

practice [4]. In addition to delivery, as the most demanding phase, postal operators continuously strive to optimize the entire parcel delivery process, both in terms of cost reduction and in terms of improving service quality. In the available literature, numerous studies can be found that address the improvement of postal system performance, most often through the analysis of the current state and the identification of directions for further development [5].

In addition to economic sustainability, which has a direct internal impact on the company, postal operators today are under increasing pressure to preserve and improve sustainability in both the social and environmental dimensions. The social aspect primarily implies ensuring the territorial, temporal, and economic availability of postal services to users, as well as the inclusion of different social strata and groups within the postal system. Human impacts on the environment vary in origin, type, and intensity, but in many forms they cause significant negative consequences. Their mitigation or elimination represents a highly relevant task at the global level. One of the most significant negative impacts relates to the emission of harmful gases, generated as a product of fossil fuel combustion in transport [6]. The use of fossil fuels represents a growing problem, as it contributes to high levels of CO_2 emissions and requires adequate corrective measures and societal attention [7]. It is particularly important to emphasize that in logistics and postal systems, the very manner of packaging parcels can have an indirect but significant impact on the environment; i.e., inadequate or oversized packaging increases the volume and weight of the parcel, reduces the utilization of transport space, and consequently leads to the engagement of additional resources, and thus to higher emissions of harmful gases. Residues of used packaging contribute to environmental pollution. Additionally, there is a clear negative aspect in terms of increased costs. In accordance with the above, the phenomenon under consideration can be observed from two independent perspectives — as a problem of parcel packaging and the utilization of the cargo space of a transport vehicle, or as a problem of the utilization and use of parcel packaging. In both cases, appropriate solutions can have a positive effect on the sustainability of the entire parcel delivery system. When discussing the improvement of cargo space utilization, it is based on the application of various algorithms that solve the task known in the literature as the 3D bin-packing problem. The objective is to distribute, that is, to pack postal items as efficiently as possible into a limited space, such as the cargo space of a postal vehicle or container, in order to reduce the number of trips and thereby increase the efficiency of the entire delivery process [8].

In this paper, the focus is directed toward a review of sustainable packaging solutions, with the aim of raising awareness regarding the improvement of sustainability and the consideration of effects within postal systems. The results of the analysis of the contribution to improving the sustainability of the postal system are presented for three selected sustainable packaging solutions: recyclable packaging, reusable packaging, and precisely dimensioned packaging (i.e., real-size). In addition, an illustrative numerical example is presented through which the impact of optimized packaging solutions can be observed.

2. Introduction

Research studies in the field of the use of sustainable packaging encompass a set of different topics. The studies mainly deal with various forms of packaging optimization, such as adjustment of package dimensions, standardization, material composition and recycling, reusable packaging in logistics, and similar. In the literature, numerous studies can be found related to the use of recycled packaging, which has been a trend in logistics chains for a longer period of time [9,10]. One of the prominent trends also relates to the concept of reusable and returnable packaging. A brief overview of selected studies related to the use of reusable packaging in different areas of logistics is presented

below. It is first necessary to define the difference, that is, the relationship between returnable and reusable packaging. Reusable packaging can be used multiple times, without the mandatory return to the same sender or operator. On the other hand, reusable packaging that is returned into the system (i.e., to the sender, operator, etc.) for reuse is returnable packaging, where the organization of reverse logistics is of great importance. Namely, every returnable packaging is reusable, but not every reusable packaging is automatically returnable.

Sarkar *et al.* [11] addressed the development of a closed-loop supply chain model for returnable transport packaging made of self-healing polymers, with the aim of improving economic and environmental sustainability. The model uses a multi-criteria approach that simultaneously maximizes profit and minimizes emissions, with the application of metaheuristic methods. Na *et al.* [12] analyzed the use of returnable packaging in the automotive supply chain. The optimal number of returnable packaging units was determined under conditions of uncertain demand and variable time parameters of reverse logistics. Using simulation experiments and sensitivity analysis, it was determined that a larger initial procurement of returnable packaging is more profitable when operations are long-term, while the benefit decreases when the operating period is short and uncertainty is high.

In the study by Liu *et al.* [13], the analysis went a step further in the operational sense. The authors examined the case of companies that rent reusable packaging. The paper analyzes the management of reusable packaging from the perspective of these companies, proposing a sharing strategy for the optimization of daily distribution and routing processes. Based on a case study of a Chinese company, a decision-support framework was developed that optimizes flows and vehicle routes. Empirical results show that the proposed approach reduces transport costs by 28.1% and simultaneously brings environmental and social benefits through shorter travel distances. Regarding the management of returnable packaging [14], a FlexSim simulation was used. It was shown that the introduction of returnable packaging and its well-organized transfer improved operational efficiency and reduced costs.

Numerous studies are dedicated to the impact of returnable packaging on improving sustainability within logistics systems, especially after the expansion of e-commerce [15]. When it comes to parcel delivery and reusable packaging, studies are mainly associated with the delivery of express items. Zhou *et al.* [16] stated that the delivery of express items in China, as well as worldwide, was experiencing expansion and that in 2021 alone, the number of deliveries exceeded 108 billion. Due to the growing demand for packaging and the accompanying environmental pressures, the wide application of reusable postal packaging has become key to promoting the concept of reduce, reuse, recycle (3R). In the study, a life cycle analysis was conducted, and a comparison of the environmental impact of reusable packaging with traditional packaging was performed. Five scenarios were defined, including conventional plastic bags and cardboard boxes, as well as reusable bags and boxes. The results show that the use of reusable packaging bags reduces the negative environmental impact by 59% compared to waste incineration and by 26% compared to the recycling of plastic bags. Reusable packaging boxes have a 63% lower negative environmental impact compared to traditional cardboard boxes. The study results also show that, in order to reduce pollution and greenhouse gas emissions, reusable boxes and bags should be used at least five and fifteen times, respectively.

Sun [17] stated that e-commerce significantly contributes to environmental pollution due to the large amount of packaging waste. As a response, the application of reusable packaging is also proposed. It is also noted that the wide application of reusable packaging faces significant challenges, primarily high initial investment costs and recycling. In order to overcome these challenges, improve the efficiency of resource use, and reduce the mismatch between supply and demand, inventory

sharing is highlighted as an effective measure. It is emphasized that sharing reusable packaging between operators facilitates overcoming the problems of high initial investments and a complex recycling process, thereby encouraging wider application and sustainability of this concept. The study [18] deals with the development of a model for the comparative analysis of CO_2 emissions of single-use and reusable packaging for parcel delivery, which was then applied to two reusable packaging systems currently available on the market. The results show that there are significant differences in the calculated CO_2 emissions of the analyzed single-use and reusable packaging, where reusable packaging becomes a better option after only a few uses.

Examples from the practice of postal operators are presented below, including the company Amazon, and their solutions in the field of sustainable packaging for parcel delivery. Within the company DHL, it is stated that the global sustainable packaging market is expected to reach 418.6 billion dollars by 2027, while 85% of consumers state that sustainable packaging influences their decisions on purchasing and using services [19]. Regulatory pressures are also increasing, as governments worldwide introduce stricter requirements [20]. Sustainable packaging implies reducing environmental impact throughout the entire product life cycle — from sourcing and production to delivery and disposal. This means the use of materials and designs that reduce waste and emissions and keep resources in circulation as long as possible [21]. There are several types of sustainable packaging, including recyclable, compostable, biodegradable, reusable, minimalist packaging, and packaging with recycled content. Such solutions help reduce environmental impact, attract environmentally conscious consumers, decrease waste, and optimize the use of space during transport [22]. Although sustainable packaging may appear more expensive initially, in the long term, it brings savings through lighter materials, reduced material usage, the durability of reusable solutions, and the avoidance of penalties related to new regulations. The company offers packaging optimization solutions and reliable sources of sustainable materials to external partners in order to overcome barriers such as cost, material performance, scalability, and availability.

The company FedEx actively develops and uses sustainable packaging as part of its strategy for emission reduction and improvement of environmental responsibility. The company offers packaging that is fully recyclable, as well as products made from recycled content, thereby contributing to the reduction of primary resource use. Special emphasis is placed on reusable packaging, including the scenario of reverse packaging flow, which reduces the amount of waste and the overall environmental footprint. FedEx insists on optimal material use, designing packaging with the minimum necessary amount of material (right-size your packaging) in order to reduce mass, volume, and resource consumption, while maintaining the required level of content protection during transport. Through its Packaging Lab, the company enables customers to perform free packaging performance testing, thereby ensuring that sustainable packaging meets technological and logistical requirements under real transfer conditions. All these activities are part of the broader FedEx strategy aimed at achieving CO_2 emission neutrality by 2040, in which sustainable packaging represents one of the key elements [23].

The United Parcel Service (UPS) is also committed to improving the circular economy through sustainable packaging practices. This implies waste reduction, increased recyclability, and the use of renewable materials. The company is also working on improving its reverse logistics systems to enable better reuse of packaging and more efficient return of materials into the recycling flow. China became the first country within the UPS network to introduce biodegradable packaging bags into its operations, which decompose within 180 days through composting. The company's goal is that, by the end of this year, 100% of packaging will be recyclable.

The company Amazon delivers a large number of parcels daily, with priority given to fast and safe delivery with as little packaging as possible. In order to reduce waste, scientifically based approaches are used to provide appropriately dimensioned, recyclable, and scalable packaging. The optimization and recycling improvement strategy also includes packaging for Amazon devices. The packaging strategy is based on four principles [24]:

i. Avoiding additional packaging by shipping products in the original manufacturer's packaging whenever possible — the Ships in Product Packaging approach. Using machine learning, an increasing number of items suitable for this approach is identified. In 2024, 12% of all packages globally were delivered without additional Amazon packaging. More than 1 billion orders globally have been delivered without additional Amazon packaging since 2019. Since 2015, packaging reduction programs have helped Amazon avoid more than 4 million tons of packaging material;
ii. When additional packaging is required, preference is given to lighter and more compact solutions. Artificial intelligence is also used to identify additional optimization opportunities. In Europe, automated packaging machines have been installed that create packaging tailored to each order. These machines use sensors to measure the exact dimensions of the product and form a customized paper bag or box, depending on the level of protection required. This means less empty space, less material used, and packaging that is easier to recycle. The machine directly applies the shipping label, making the package ready for immediate dispatch;
iii. Preference is given to materials that can be recycled in households, while efforts are simultaneously made to reduce single-use plastics. One hundred percent of packaging material in Europe and India can be recycled in households, while in the USA and Canada, 99.7% of mailing envelopes have been replaced with recyclable paper alternatives;
iv. Continuous cooperation with partners from the public and private sectors in order to develop and implement more sustainable packaging solutions and improve the global recycling infrastructure.

3. Analysis of the Contribution to Sustainability Improvement of Selected Solutions

The following presents the results of the analysis of the contribution to improving the sustainability of the postal system for three selected sustainable packaging solutions:

i. recyclable packaging (Table 1);
ii. reusable packaging (Table 2);
iii. precisely dimensioned packaging (Table 3).

It is important to emphasize that these approaches complement each other. It is desirable that reusable and real-size packaging be made of recyclable materials, thereby further increasing their positive effect on reducing waste, costs, and the overall negative environmental impact. The analysis is structured in accordance with the three dimensions of sustainability (i.e., environmental, economic, and social) to systematically examine the direct and indirect effects of each of the listed approaches. The views and opinions presented in the following tables are the result of the authors' assessment, taking into account relevant literature, examples of good practice, and professional experience in the field of postal and logistics systems.

Table 1
Overview of the contribution to sustainability improvement – recyclable packaging

Sustainability dimension	Characteristics and activities	Effects and contribution to sustainability
Environmental	– Packaging that is easily recyclable; – Use of recycled material; – Sorting and disposal into existing recycling streams.	– Lower need for primary raw materials; – Less waste that is difficult to recycle; – Lower CO_2 emissions; – Strengthening the circular economy.
Economic	– Often lower procurement cost compared to reusable packaging; – Rapid implementation without major infrastructure changes; – Incentives for the procurement of recyclable materials.	– Reduced waste disposal costs; – No reverse logistics costs; – Potentially lower total costs due to lower material prices, subsidies, incentives, and bonuses.
Social	– Transparent and easily understandable sustainable solution; – Familiarization of service users with the materials used; – Promotions and instructions for packaging disposal.	– High level of acceptance by users; – Encouragement of proper waste disposal habits; – Reduction of pollution in the urban environment; – Positioning of the postal operator as environmentally responsible; – Raising awareness in society about the importance of recycling processes.

Table 2
Overview of the contribution to sustainability improvement – reusable packaging

Sustainability dimension	Characteristics and activities	Effects and contribution to sustainability
Environmental	– Boxes, envelopes, and pouches intended for multiple use; – Establishment of a reverse packaging flow (collection, cleaning, redistribution); – Reduction of single-use packaging production.	– Significant reduction in the amount of packaging waste; – Overall lower CO_2 emissions compared to single-use packaging after a certain number of use cycles; – Reduction of the negative effects of packaging waste disposal.
Economic	– Higher initial production cost, but distributed over a larger number of use cycles; – Reverse logistics; – Greater packaging durability reduces damage to contents.	– Long-term savings through multiple use; – Reduction of complaint costs due to fewer damaged parcels; – Well-organized reverse logistics can have a positive impact on costs.
Social	– Operator's environmental commitment; – Better protection of the parcel; – Education on the importance of packaging reuse.	– Reduction of waste in local communities; – Increased trust in the company; – Positioning of the postal operator as environmentally responsible; – Raising awareness in society about the importance of packaging reuse.

Table 3
Overview of the contribution to sustainability improvement – precisely dimensioned packaging (real-size)

Sustainability dimension	Characteristics and activities	Effects and contribution to sustainability
Environmental	– Packaging dimensioned according to the dimensions of the parcel; – Lower volume and mass of the packed parcel; – Smaller amount of cushioning material used.	– More efficient utilization of cargo space (lower CO_2 emissions per parcel); – Material savings and less waste.
Economic	– Less material required.	– Lower material procurement costs; – More efficient utilization of cargo space (lower transport and storage costs).
Social	– Better user experience (more compact packages, less waste when opening); – Education on the importance of rational material use.	– Higher level of user satisfaction; – Positioning of the postal operator as environmentally responsible; – Reduction of waste in local communities; – Raising awareness in society about the importance of rational material use.

Below is an illustrative numerical example of the contribution to the sustainability of the postal system in the case of applying the precisely dimensioned packaging approach, expressed through savings in material used for production, that is, waste. The quantity of this material has a direct impact on the amount of waste, as well as on its procurement costs. For the calculation of the contribution defined in this way, a formula for determining the relative reduction of packaging mass was derived:

$$r_m = \frac{m_{\text{old}} - m_{\text{new}}}{m_{\text{old}}} \cdot 100\% \tag{1}$$

where r_m is the relative reduction of packaging mass, expressed in percentages, m_{old} is the mass of the previous (standard) packaging before the introduction of the real-size solution, and m_{new} is the mass of the new, precisely dimensioned (real-size) packaging.

In order to determine the indicator of annual material savings, that is, waste, the following formula was derived:

$$\Delta M_{\text{year}} = (m_{\text{old}} - m_{\text{new}}) \cdot N \tag{2}$$

where ΔM_{year} annual material or waste savings (in kilograms or tons), m_{old} is the mass of the previous (standard) packaging before the introduction of the real-size solution, and m_{new} is the mass of the new, precisely dimensioned (real-size) packaging and N – the number of observed parcels on an annual level.

Based on Eq. (1) and Eq. (2), as well as the adopted value of the mass of the previous (standard) packaging before the introduction of the real-size solution ($m_{\text{old}} = 60$ g), which is aligned with the official information of postal operators for an envelope measuring 270 × 350 mm, as well as the mass

of the new, precisely dimensioned real-size packaging (adopted value $m_{\text{new}} = 50$ g), indicators illustrating the contribution to improving the sustainability of the postal system were calculated. Express items in domestic traffic were analyzed, which, according to the data of the Universal Postal Union for 2023, amounted to 11.967.142. For the purposes of this calculation, the assumption was adopted that the specified real-size packaging can be applied to 30% of parcels, which amounts to N = 3.590.143 parcels.

Based on the data in the given example, the relative reduction of packaging mass amounts to r_m = 16.7%, while the annual material or waste savings amount to ΔM_{year}= 35.901 kg, that is, approximately 36 t. It should be emphasized once again that, for the calculation of this indicator, only 30% of express items in domestic traffic were taken into account. Therefore, the total savings would be significantly higher if the analysis were extended to other types of parcels and packaging. Additionally, the difference between m_{old} and m_{new} in many cases may be even greater, which would further increase the total material and waste savings.

Based on the available data of the Universal Postal Union on the number of express items in domestic traffic for the five-year interval 2019–2023, keeping the other parameters from the previous example (type of packaging, m_{old}, m_{new} , 30% of the number of express items in domestic traffic), the indicators of annual material or waste savings were obtained and are shown in Figure 1.

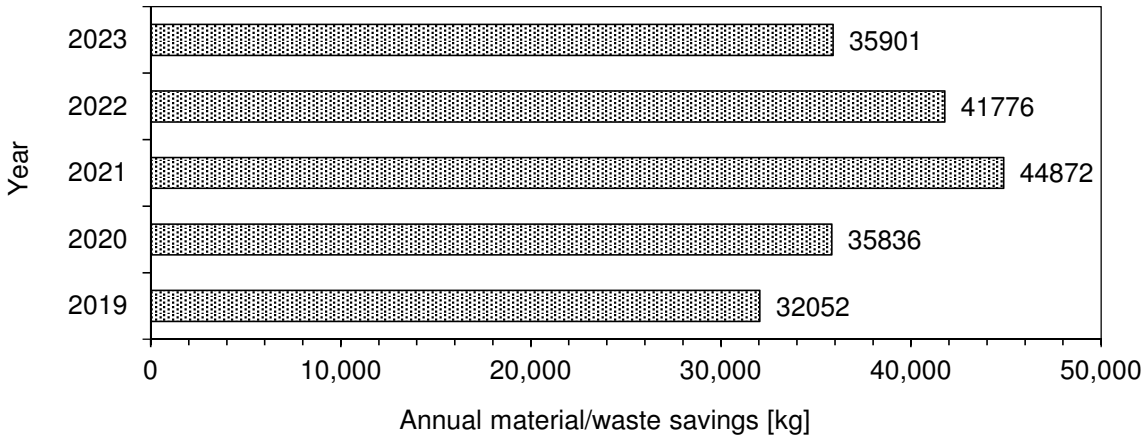

Fig. 1. Annual material/waste savings for the period 2019 – 2023

Based on the obtained results, it is straightforward to conclude that, in accordance with the defined parameters, the total material/waste savings for the analyzed five-year period would amount to 190,437 kg (≈ 190 t). As stated in the earlier discussion, the savings could be significantly higher if all real indicators were taken into account.

4. Conclusion

The introduction of various sustainable packaging solutions and packaging optimization into parcel delivery systems represents a very important step toward improving the sustainability of the entire system. Owing to such an approach and the implementation of different solutions, it is possible to better plan resources, achieve economic savings, and contribute to environmental protection, which all indirectly have a positive impact on society as a whole. At the same time, through responsible behavior, the company is better positioned in the market and gains additional trust from users. On the other hand, the different solutions that can be implemented also require certain additional activities, such as planning recycling programs, organizing reverse logistics, procurement of equipment, and training of personnel for precise packaging, etc.

The paper provided a brief overview of the contribution to sustainability improvement for three selected sustainable packaging solutions: recyclable packaging, reusable packaging, and precisely dimensioned packaging (real-size). In addition, through an illustrative numerical example, a significant potential for improving sustainability through packaging optimization is demonstrated.

Future research may contribute to the development of more sustainable solutions, which will further shape global logistics and respond to the growing demands of the modern market.

Conflict of Interest

The authors declare no conflict of interest.

Acknowledgment

The authors received no external funding for this research.

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