Shi, Y., Lin, Y., Wang, S., Wen, H., Lim, M. K. and Tseng, M.-L. (2023) Resource saving and carbon footprint reduction potential of urban symbiosis strategy in express packaging waste recycling network. *Waste Management*, 161, pp. 17-28. (doi: 10.1016/j.wasman.2023.02.023)

Reproduced under a Creative Commons License.
https://creativecommons.org/licenses/by-nc-nd/4.0/

This is the author version of the work. There may be differences between this version and the published version. You are advised to consult the published version if you want to cite from it:
https://doi.org/10.1016/j.wasman.2023.02.023

https://eprints.gla.ac.uk/292804/

Deposited on 24 February 2023

Enlighten – Research publications by members of the University of Glasgow
https://eprints.gla.ac.uk

Resource saving and carbon footprint reduction potential of urban symbiosis strategy in express packaging waste recycling network

Yuhe Shi [a], Yun Lin [a,*], Songyi Wang [b, c], Haolin Wen [d], Ming K. Lim [e], Ming-Lang Tseng [f,g]

[a] School of Management Science and Real Estate, Chongqing University, Chongqing, China

[b] Department of Statistics and Data Science, Southern University of Science and Technology, Shenzhen, China

[c] Peng Cheng Laboratory, Shenzhen, Guangdong, China

[d] Department of Management Engineering and Equipment Economics, Naval University of Engineering, Wuhan, China

[e] Adam Smith Business School, University of Glasgow, Glasgow, United Kingdom

[f] Institute of Innovation and Circular Economy, Asia University, Taiwan

[g] Department of Medical Research, China Medical University Hospital, China Medical University, Taichung, Taiwan

[*]Corresponding author: Yun Lin, linyun@cqu.edu.cn

E-mail:

Yuhe Shi: shiyuhe@cqu.edu.cn

Songyi Wang: wsy196973@163.com

Haolin Wen: 457813217@qq.com

Ming K. Lim: ming.lim@glasgow.ac.uk

Ming-Lang Tseng: tsengminglang@gmail.com

Abstract

The booming express delivery industry corresponds to the environmental challenges caused by massive express packaging waste (EPW). An efficient logistics network is necessary link to support EPW recycling. This study, therefore, designed a circular symbiosis network for EPW recycling based on urban symbiosis strategy. The treatment of EPW in this network includes reuse, recycling and replacing. An optimization model with multi-depot collaboration combining material flow analysis and optimization methods was developed and a hybrid non-dominated sorting genetic algorithm-II (NSGA-II) was designed as technical support for designing the circular symbiosis network while quantitatively assessing the economic and environmental benefits of the network. The results show that the designed circular symbiosis option has better resource saving and carbon footprint reduction potential than both the business as usual option and circular symbiosis option without service collaboration. In practice, the proposed circular symbiosis network can save EPW recycling costs and reduce carbon footprint. This study provides a practical guideline for the application of urban symbiosis strategies to help urban green governance and the sustainable development of express companies.

Keywords: urban symbiosis; express packaging waste; recycling network optimization; carbon footprint

Abbreviation

EPW	express packaging waste
UrS	urban symbiosis
IS	industrial symbiosis
BAU	business as usual
MSW	municipal solid waste
CSN-EPWR	circular symbiosis network for express packaging waste recycling
WTE	waste-to-energy
RC	recycling center
EP	express parcel
CES	community express station
CRS	community recycling site
ERS	express regional satellite
RDF	refuse derived fuel
RPF	refuse plastic & paper fuel
MDC-RLPPD	multi-depot collaboration routing location problem with pickup and delivery
NSGA-II	Non-dominated sorting genetic algorithm-II
DEA	differential evolutionary algorithm

1. Introduction

The rapid growth of online retail has propelled express delivery into one of the fastest growing industries in the world, which is critical to the countries' economic development (Fan et al., 2017; Kang et al., 2021). The number of global parcels will reach 266 billion by 2026, and massive express packages are bringing environmental problems that cannot be ignored (Duan et al., 2019; Kang et al., 2021). If there are no effective control measures, the consumption of express packaging materials in China alone will reach 41.27 million tons by 2025 (Yang et al., 2021). However, the overall recycling rate of express packaging in China is less than 20%, far below the level of 45% in developed countries (Wen et al., 2021; Xiao and Zhou, 2020) .The express delivery industry still has great potential to reduce the consumption of packaging materials (Su et al., 2020). The environmental impact caused by EPW generated in the express delivery industry has been scientifically evaluated by scholars (Duan et al., 2019). EPW consumes resources and emits carbon dioxide, heavy metals, organic and inorganic pollutants during production, distribution and handling (Fan et al., 2017). In response, it is urgent to strengthen the green governance of express packaging and alleviate the resource and environmental pressure caused by express packaging waste (EPW).

The environmental impact of EPW can be effectively mitigated through measures such as slowing delivery, fuel system upgrades, packaging material reduction, logistics optimization, and carbon pricing (Kang et al., 2021). In the context of global carbon emission reduction, express companies have implemented a variety of express packaging management measures, such as the configuration of recycling devices, the use of recyclable packaging, and express packaging reduction (Li et al., 2022a; Rubio et al., 2019). In fact, optimizing EPW recycling logistics network achieves greater resource savings and footprint reductions than using less packaging materials (Kang et al., 2021). Moreover, an efficient logistics network is a useful way and necessary link to support the application of recycling devices and recyclable packaging (Cai et al., 2021; Chaabane et al., 2021). However, existing research on EPW recycling has focused on environmental impact assessment (Duan et al., 2019; Fan et al., 2017; Su et al., 2020), recycling policies (Guo et al., 2021; Xiao et al., 2020; Yang et al., 2022; Yang et al., 2021), and consumer recycling behavior and attitudes (Dong and Hua, 2018; Hua et al., 2021). Less attention has been paid to the benefits of optimizing logistics network on EPW recycling, which limits the effectiveness of recycling and is not conducive to solving recycling problems. The forward logistics system of express parcels from express companies to consumers has developed maturely, but the reverse logistics chain of EPW recycling from consumers to express companies has not been established (Li et al., 2022a; Xiao and Zhou, 2020). The lack of an effective recycling system and high recycling costs are the main reasons for the low recycling rate of EPW (Cai et al., 2021; Duan et al., 2019). Optimization of the logistics network will help in improving the environmental impact of EPW and minimizing logistics operation costs (Hannan et al., 2018; Hannan et al., 2020; Li et al., 2022b; Wang et al., 2021). Therefore, this study incorporates the reverse activity of EPW recycling into the forward logistics system of express parcel delivery in an attempt to establish a green and efficient EPW circular network.

As a practical strategy for sustainable urban development, urban symbiosis (UrS) is an extension of industrial symbiosis (IS). IS is the exchange of raw materials, energy and other products between different industries to improve resource utilization efficiency and reduce environmental impact in industrial processes (Chertow, 2007; Colpo et al., 2022; Sellitto et al., 2021). UrS is defined as "the use of by-products (waste) from cities (or urban areas) as alternative raw materials or sources of energy in industrial activities" (Dong et al., 2014; Dong et al., 2016; Ohnishi et al., 2017; Van Berkel et al., 2009). The difference between UrS and IS lies in the scale of the systems, the goal and scope of symbiosis, and the diversity of functions(Lu et al., 2020). Considering the negative impacts of increasing municipal solid waste (MSW) on ecological environment and social health, UrS strategy is regarded as a sustainable effort to reduce waste volumes and carbon footprints (Chaker et al., 2021; Siddiqi et al., 2020). The utility of UrS in MSW management has been effectively demonstrated — combining the advantages of resource conservation, recycling, low carbon, and footprint reduction (Geng et al., 2010; Xiao et al., 2022). To optimize the metabolism of urban systems, UrS allows the use of MSW as an input to traditionally unrelated industries (Chen et al., 2012; Dong et al., 2014). In UrS systems, recyclable waste is converted into resources, ultimately achieving the goal of optimizing energy and material consumption and reducing pollution footprints (Chaker et al., 2021; Lu et al., 2020). Material flow analysis (MFA), life cycle assessment (LCA), and energy value analysis are common methods for evaluating the benefits of UrS (Dong et al., 2017; Lu et al., 2020; Sun et al., 2017) . However, in the existing UrS schemes for MSW management, EPW is only treated as part of MSW, meaning that it is used as an available resource for the industrial system together with other recyclable wastes (Xiao et al., 2022). As a recyclable resource, the economic and environmental benefits of EPW in UrS systems have not been evaluated in detail. With the escalation of express packaging consumption and waste, sustainable cities and businesses will need a more collaborative approach to promoting the resource-waste cycle in the future (Lenhart et al., 2015). Therefore, this study tries to explore the potential of UrS in the EPW green governance. To our knowledge, there is currently no research on combining UrS strategies with the optimization of EPW recycling, which also implies that the potential of related studies is great.

In view of the above discussion, the research on EPW management to be further explored includes: (1) evaluating the benefits of optimizing the logistics network for EPW recycling, (2) designing an effective EPW recycling system, and (3) exploring the application of UrS strategy in EPW recycling optimization. Therefore, this study proposes to investigate the resource saving and carbon footprint reduction performance of UrS strategy in the EPW recycling network. To achieve this goal, this study includes the following research content: (1) design a circular symbiosis network for EPW recycling (CSN-EPWR) based on UrS strategy; (2) evaluate the economic and environmental benefits of the CSN-EPWR; (3) propose a logistics optimization model with multi-depot collaborative pickup and delivery and a hybrid heuristic algorithm to support the operation of CSN-EPWR. As far as we know, this study is the first to explore the utility of UrS in EPW recycling. In theory, this study proposes to design a circular symbiosis network to improve the efficiency of EPW recycling. In addition, the mathematical model and algorithm developed in this study can provide a reference for further research on the application of UrS in green governance of urban activities. In practice, this study helps express companies to solve the problems of low EPW recycling rate, difficult recycling and transfer operation, and high costs, and further contributes to the sustainable urban development.

The rest of this study is organized as follows. **Section 2** details the design of CSN-EPWR, the associated optimization model, and the methodology used to implement the CSN-EPWR design. **Section 3** describes the results of the case study. The application of CSN-EPWR is discussed in **Section 4**. The conclusions are summarized in **Section 5**.

2. Method

2.1 Application of UrS strategy

In the business as usual (BAU) scenario, EPW is treated as MSW and mixed with other MSW (Song et al., 2022a; Xiao and Zhou, 2020). There is no separate method or network for handling EPW. However, the fact is that most of the EPW can be directly reused, and the part that cannot be reused due to damage or other causes of contamination can play a significant role in the UrS system, such as raw materials for remanufactured products or fuel for incineration to power generation.

The CSN-EPWR is designed to solve the environmental problems caused by EPW. There are urban clusters with express companies, remanufacturing firms, waste-to-energy (WTE) plants, and landfills in the CSN-EPWR. And the recycling center (RC) of express companies is a vital player in the CSN-EPWR. Several express companies form an alliance to carry out collaborative services in the last-mile delivery, and delivering the express parcels (EP) to community express stations (CES) while picking up EPW placed by customers at community recycling site (CRS). EPW can be divided into paper and plastic in this study (Duan et al., 2019; Song et al., 2022b) . All EPW is shipped to the RC and sorted in the RC for further treatment: (1) reuse, the intact EPW that can be directly reused, such as intact cartons, is temporarily stored in the RC and will be called by the express regional satellites (ERS); (2) recycling, recyclable materials, such as damaged paper EPW, are sent to remanufacturing firms to be used as raw materials to make new express packaging or other paper-based products, and the finished products are reused by ERS; (3) replacing, end-of-life materials are sent to WTE plants to make refuse plastic & paper fuel (RPF) to replace coal as a fuel for power generation, and the resulting electricity can be used to support the operation of RC and remanufacturing firms. The system boundary is shown in **Fig.1**.

The application of UrS strategy enables each express packaging to be fully used in the life cycle. Different subjects are connected to each other through UrS activities, and there are material and energy exchanges within the system. EPW is generated and cleared in the CSN-EPWR.

To demonstrate that the proposed CSN-EPWR is an efficient method, three different options for EPW recycling were set. Option 1 is the BAU scenario, which assumes that the EPW treatment system is no different from the way it is currently used. Each express company's ERS operates independently to deliver express parcels. EPW is mixed with MSW at the community waste stations, the disposal channels include: (1) picked up by the 'garbage man' (scavengers, residents, cleaning staff, etc.) and sent to the waste recycling stations, from where it is transported to the remanufacturing plant for the production of products with economic value; (2) transferred by garbage trucks to waste transfer stations for pretreatment and landfill, or using refuse derived fuel (RDF) technology to separate the non-combustibles materials in MSW from the waste stream for incineration power generation after processing steps of hammering, shredding, and hydropulping (Longo et al., 2020). Based on Option 1, option 2 is a solution from the perspective of UrS, which introduces UrS activities to centralize EPW treatment. However, there is no service collaboration between ERSs belonging to different express companies, and the delivery of express parcels and the pickup of EPW are carried out separately. Option 3 is a solution corresponding to CSN-EPWR, where multiple express companies cooperate in pickup and delivery activities, and EPW participates in UrS activities (reuse, recycling, and recycling) after being classified by RC. Different from the traditional MSW-based RDF, the EPW-based RPF technology in CSN-EPWR is to make solid fuels from waste paper and plastic and then use them as substitutes for fossil fuels (Geng et al., 2010; Xiao et al., 2022). It has the advantages of convenient operation, economic savings, and stable quality (Dong et al., 2018), which helps to achieve more savings. **Fig. 2** illustrates the treatment process for the three options.

2.2 Benefits analysis

The raw material savings and waste reduction resulting from the implementation of CSN-EPWR can be quantified by MFA that is a basic method for identifying and quantifying the matter and energy flow in a network (Sun et al., 2017). Based on the analysis of the different types of material and energy flows in the system, the avoided resource consumption and waste footprint can be determined to quantify the economic and environmental benefits of the system. In order to clearly quantify the impact of each link from EPW generation to disposal in CSN-EPWR, the economic and environmental benefits are calculated separately according to the logistics process and different disposal methods (Song et al., 2022a; Xiao and Zhou, 2020). The detailed definitions and values of the parameters are listed in **Table S1** of the Supplementary Material.

(1) Economic benefits

EPW consumes resources during the flow process and saves corresponding resources due to participation in UrS activities. Therefore, the economic benefits are quantitatively assessed by calculating the used costs (C) and the resources costs saved by UrS activities (P). Specifically, the used costs can be divided into two main components.

① **EPW collection costs** (C_1). It refers to the used costs from the generation of EPW until it flows out of RC.

$$C_F = c_{vf} \sum_{s \in S} \sum_{k \in K_s} u_{sk} \tag{1}$$

$$C_V = c_{ele} \left(\sum_{s \in S} \sum_{k \in K_s} \sum_{i,j \in P} u_{sk} x_{ij}^{sk} EC_{ij} d_{ij} \right) + c_s \sum_{i \in N} (q_{Wi} + p_{Wi}) + c_{rc} \sum_{i \in N} p_{Wi} \tag{2}$$

$$C_1 = C_F + C_V \tag{3}$$

Where the **Eq. (1)** calculates the costs of using the vehicles (C_F). The variable costs (C_V) that involves the transportation costs, the service costs and the operating costs of RC, the detailed equation is shown in **Eq. (2)**. Transportation costs are influenced by energy consumption. The energy consumption per unit distance of the vehicle on the arc (i, j) can be expressed as $EC_{ij} = 2.8 * 10^{-4} ef_m ef_d \left(a_{ij} \left(CW_{sk} + l_{Wij}^{sk} \right) + \beta \left(0.28 s_k \right)^2 \right)$ (Basso et al., 2019; Bektaş and Laporte, 2011; Zhang et al., 2018). a_{ij} is the arc-specific factor, β is the vehicle-specific factor. Service costs are the costs of vehicle delivery and pickup to the nodes. To implement the CSN-EPWR scenario, an RC is required for handling EPW, so the operating costs of the RC needs to be considered. The operating costs refer to the costs generated by the classification and temporary storage of EPW in RC, including the use costs of equipment and labor costs. The service costs and operating costs are related to the treatment volume. **Eq. (3)** represents the total EPW collection costs.

② **EPW recycling costs** (C_2). It refers to the costs incurred by EPW participating in UrS activities after classification is completed in the RC.

$$C_T = c_{vu} \sum_{\chi \in D} \left(W_\chi / Q_\chi \right) + c_{fuel} \sum_{m \in M} \sum_{\chi \in D} \left(W_\chi / Q_\chi \right) \rho_\chi^* d_{m\chi} \tag{4}$$

$$C_{TR} = \sum_{\chi \in D} c_{u\chi} W_\chi \tag{5}$$

$$C_2 = C_T + C_{TR} \tag{6}$$

Where the transportation costs (C_T) refer to the costs of using vehicles to transport EPW to remanufacturing plants, WTE plants and landfills, including apportioned vehicle use costs and energy costs, as shown in **Eq. (4)**. The treatment costs (C_{TR}) are the costs incurred by the remanufacturing plants, WTE plants and landfills to process the EPW, as shown in **Eq. (5)**. The amount of bottom ash to be landfilled, $W_{p+3} = R_{ag} W_{p+2}$, is related to the amount of waste incineration. R_{ag} is the bottom ash generation rates. **Eq. (6)** represents the total EPW recycling costs.

The resources costs saved by UrS activities in CSN-EPWR consist of four components.

$$P_{DC} = c_{lc} f_{circular} R_{circular} \sum_{i \in N} p_{Wi} \tag{7}$$

$$P_{RM} = c_{\text{material}} f_{\text{material}} W_{p+1} + c_{ele} f_{energy} W_{p+1} \tag{8}$$

$$P_{IPG} = c_{coal} f_{RPF} R_{RPF} W_{p+2} \tag{9}$$

$$P_L = c_l R_L \sum_{i \in N} p_{Wi} \tag{10}$$

$$P = P_{RM} + P_{IPG} + P_{DC} + P_L \tag{11}$$

Where **Eq. (7)** calculates the saved costs from direct reuse of EPW (P_{DC}), which is the full life-cycle costs of express packaging from raw materials collection to the finished product before it leaves the factory. **Eq. (8)** calculates the saved costs from EPW remanufacturing (P_{RM}). Raw materials (e.g., wood) and energy costs are reduced by producing recycled products from waste paper. **Eq. (9)** calculates the saved costs from RPF incineration for power generation (P_{IPG}), which specifically refers to the resource saving from using EPW-based RPF as fuel for power generation. **Eq. (10)** calculates the saved costs from EPW landfill (P_L). MSW landfill costs are avoided after EPW recycling. The calculation of total saved resources costs is given by **Eq. (11)**.

Based on the above analysis, the final economic benefits (net costs) of CSN-EPWR can be calculated as:

$$\varDelta C = C_1 + C_2 - P \tag{12}$$

(2) Environmental benefits

Environmental benefits mainly refer to the carbon footprint reduction potential of the system. Similarly, environmental benefits are measured in terms of carbon footprint generated (E) and carbon footprint avoided by UrS activities (AE).The carbon footprint generated by CSN-EPWR result from transportation, operation of RC, recycled EPW remanufacturing, and RPF incineration for power generation.

$$E_T = e_{ele}\left(\sum_{s\in S}\sum_{k\in K_s}\sum_{i,j\in P} u_{sk} x_{ij}^{sk} EC_{ij} d_{ij}\right) + e_{fe}\left(\sum_{m\in M}\sum_{\chi\in D}\left(W_\chi / Q_\chi\right)\rho_\chi^* d_{m\chi}\right) \tag{13}$$

$$E_{RC} = e_{blc} S_{RC} \sum_{m\in M} B_m \Big/ 365 l_{RC} \tag{14}$$

$$E_{RM} = e_{ele} A_D W_{p+1} \tag{15}$$

$$E_{IPG} = e_{RPF} R_{RPF} W_{p+2} \tag{16}$$

$$E = E_T + E_{RC} + E_{RM} + E_{IPG} \tag{17}$$

Where carbon footprint from transportation (E_T) is related to unit energy consumption and include two stages of EPW collection and EPW recycling, as shown in **Eq. (13)**. e_{fe} is the carbon footprint factor of fuel, $e_{fe} = NCV \times CC \times OF \times (44/12)$. **Eq. (14)** calculates the carbon footprint from the operation of RC (E_{RC}), which is estimated based on the scale of facility, including the production phase of building materials, the construction phase and the operation phase of facility (Huo et al., 2021). The carbon footprint from EPW remanufacturing (E_{RM}) is calculated by **Eq. (15).** A_D is the unit energy consumption for EPW remanufacturing. **Eq. (16)** calculates carbon footprint from RPF incineration for power generation (E_{IPG}). **Eq. (17)**

indicates the total generated carbon footprint.

The carbon footprints avoided by UrS activities can also be divided into four components.

$$AE_{DC} = e_{lc} f_{circular} R_{circular} \sum_{i \in N} p_{Wi} \tag{18}$$

$$AE_{RM} = e_{\text{material}} f_{\text{material}} W_{p+1} \tag{19}$$

$$AE_{IPG} = e_{coal} f_{RPF} R_{RPF} W_{p+2} \tag{20}$$

$$AE_{L} = e_{l} R_{L} \sum_{i \in N} p_{Wi} \tag{21}$$

$$AE = AE_{DC} + AE_{RM} + AE_{IPG} + AE_{L} \tag{22}$$

Where **Eq. (18)** calculates the avoided carbon footprint from direct reuse of EPW (AE_{DC}), which refers to the reduced full life cycle carbon footprint of new express packaging by directly reusing intact EPW. **Eq. (19)** calculates the avoided carbon footprint from EPW remanufacturing (AE_{RM}). The implicit carbon footprint of raw materials is reduced by EPW remanufacturing. **Eq. (20)** calculates the avoided carbon footprint from RPF incineration for power generation (AE_{IPG}), which is the reduced carbon footprint in the application of RPF. **Eq. (21)** calculates the avoided carbon footprint from landfill (AE_{L}). EPW participation in UrS activities avoids the carbon footprint of being landfilled as MSW. The calculation of total avoided carbon footprint is given by **Eq. (22)**.

Therefore, the final environmental benefits (net footprint) of CSN-EPWR can be calculated as:

$$\Delta E = E - AE \tag{23}$$

2.3 Design of the CSN-EPWR

An optimization model for multi-depot collaboration routing location problem with pickup and delivery (MDC-RLPPD) is proposed for designing CSN-EPWR to ensure the rational utilization of logistics resources and improve the efficiency of EPW recycling and scheduling. In the traditional distribution network of express parcels, the relatively independent logistics operation may cause resources waste and environmental impact (Shi et al., 2022a; Wang et al., 2021). If the EPW recovery link is added, new logistics resources need to be assigned, which increases the operation costs. In addition, the location of RC is crucial to the design of CSN-EPWR. The CSN-EPWR in this study aims to enhance the economic and environmental benefits of EPW recycling by establishing service collaboration between facilities of different express companies. Therefore, multi-depot collaboration, pickup and delivery operations, and joint optimization of routing and location are considered simultaneously in the MDC-RLPPD model.

Regarding the comparison of logistics operation modes with service collaboration and non-service collaboration, as shown in **Fig. 3**, the main differences are in two aspects: First, whether the ERSs of different express companies operate independently; Second, whether the pickup and delivery operations are completed simultaneously. Every CES (CRS) has express parcels delivery and EPW pickup requirements. This study assumes that CES and CRS are adjacent to each other. In a logistics network with non-service collaboration, as shown in **Fig.3(a)**, each ERS operates independently to serve all CESs (CRSs) in the network, and pickup and delivery operations are performed separately. Duplicate pickup and delivery paths result in inefficient use of resources. In a logistics network with service collaboration, as shown in **Fig.3(b)**, each ERS forms a service cluster with multiple CESs (CRSs). The pickup and delivery services of each CES (CRS) are performed simultaneously by one vehicle of the ERS. The vehicle has to transport EPW to the RC before returning to the ERS.

The MDC-RLPPD model tries to optimize the design of CSN-EPWR to improve economic and environmental benefits. The expenditure part of the economic and environmental benefits analyzed in **Section 2.2** is used as the optimization objectives of the model, that is, the used costs (C) and the generated carbon footprint (E), as shown in **Eq. (24) - (25)**.

$$\min C = C_F + C_V + C_T + C_{TR} \tag{24}$$

$$\min E = E_T + E_{RC} + E_{RM} + E_{IPG} \tag{25}$$

This study organizes the constraints into three groups, some general constraints are listed in the **S1.1** of the Supplementary Material.

$$x_i^s - \sum_{j\in N\cup M}\sum_{k\in K_s} x_{ij}^{sk} \ge 0 \qquad \forall i\in N, s\in S \tag{26}$$

$$B_m - x_{im}^{sk} \ge 0 \qquad \forall m\in M, i\in N, s\in S, k\in K_s \tag{27}$$

$$\sum_{k\in K_s} x_{ij}^{sk} = 0 \qquad \forall i\in S, j\in S, s\in S \tag{28}$$

$$\sum_{s\in S}\sum_{k\in K_s}\sum_{i\in S\cup N} x_{ij}^{sk} = 1 \qquad \forall j\in N, i\ne j \tag{29}$$

$$\sum_{i\in N}\sum_{j\in M} x_{ij}^{sk} - \sum_{j\in M} x_{js}^{sk} = 0 \qquad \forall k\in K_s, s\in S \tag{30}$$

$$\sum_{m\in M} B_m \le M_n \tag{31}$$

(1) Route constraints. Constraint (26) emphasizes that the route is feasible only when the CES i is served by the ERS s. Constraint (27) requires that the location of the unopened RC will not be passed by vehicles. Constraint (28) indicates that ERSs cannot serve each other. Constraint (29) restricts each CES to be visited only once. Constraint (30) forces the vehicle

to go through the RC and back to the ERS. Constraint (31) limits the number of RCs that can be opened.

$$D_{Wli}^{sk} + P_{Wli}^{sk} \le Q_{sk} \qquad \forall i \in N, j \in N \cup M, k \in K_s, s \in S \tag{32}$$

$$D_{Vli}^{sk} + P_{Vli}^{sk} \le V_{sk} \qquad \forall i \in N, j \in N \cup M, k \in K_s, s \in S \tag{33}$$

(2) Load constraints. Constraints (32) and (33) require that the sum of delivery and pickup demands on each arc does not exceed the maximum payload and capacity of the vehicle.

$$t_i^{sk} + \lambda \sum_{i \in S \cup N} \left(q_{Wi} + p_{Wi}\right) + \left(d_{ij} / s_k\right) \le G\left(1 - x_{ij}^{sk}\right) + t_j^{sk} \qquad \forall i \in S \cup N, j \in N, i \ne j, k \in K_s, s \in S \tag{34}$$

$$t_j^{sk} + \lambda P_{Wli}^{sk} \sum_{i \in N} x_{ij}^{sk} + \left(d_{js} / s_k\right) \le G\left(1 - x_{js}^{sk}\right) + t_s^{sk} \qquad \forall j \in M, k \in K_s, s \in S \tag{35}$$

$$\eta_i^{sk} + EC_{ij} d_{ij} \le G\left(1 - x_{ij}^{sk}\right) + \eta_j^{sk} \quad \forall i,\ j \in P, i \ne j, s \in S, k \in K_s \tag{36}$$

$$B_m, u_{sk}, x_i^s, x_{ij}^{sk} = \{0,1\} \qquad m \in M, k \in K_s, s \in S, i \in P, j \in P \tag{37}$$

$$l_{Wij}^{sk}, \eta_i^{sk}, D_{Wai}^{sk}, D_{Wli}^{sk}, P_{Wai}^{sk}, P_{Wli}^{sk}, D_{Vai}^{sk}, D_{Vli}^{sk}, P_{Vai}^{sk}, P_{Vli}^{sk}, t_i^{sk} \ge 0 \quad k \in K_s, s \in S, i \in P, j \in P \tag{38}$$

(3) Time and energy consumption constraints. Constraints (34) and (35) represent the time relationship between the nodes. Constraints (36) establish the energy consumption relationship between nodes. Constraints (37) and (38) denote the variables domain.

2.4 Implementation of the CSN-EPWR

The design of CSN-EPWR is constructed as a bi-objective mixed-integer programming model — MDC-RLPPD. A suitable algorithm is required to transform the mathematical model into an executable solution. For the solution of optimization problems with multiple objectives in a large-scale logistics network, multi-objective heuristic algorithms are effective methods to search Pareto optimal solutions (Ma et al., 2021; Wang et al., 2021). Non-dominated sorting genetic algorithm-II (NSGA-II) is an extension of the traditional genetic algorithm by introducing elite strategy, crowding degree estimation strategy and fast non-dominated sorting strategy (Deb et al., 2002), which is widely used in many fields for multi-objective problems (Xu et al., 2022; Yadav et al., 2022; Zhao et al., 2019). In particular, research on related improved algorithms has demonstrated the performance of NSGA-II to search for Pareto optimal solutions in solving bi-objective optimization problems (Maskooki et al., 2022; Rabbani et al., 2017; Shi et al., 2022b). Therefore, this study designs a hybrid NSGA-II (HNSGA-II) based on the general differential evolutionary algorithm (DEA) and NSGA-II framework for the proposed bi-objective MDC-RLPPD model, and the solution process includes two stages: service cluster partition with multi-depot collaboration, and symbiosis network optimization. **Fig. 4** illustrates the computational flow of the algorithm. The detailed algorithm and related technical terms are described in **S1.2** of the Supplementary Material.

To illustrate the performance of the designed HNSGA-II in implementing the MDC-RLPPD model, this paper used Cordeau data as benchmark to generate the test instances (Cordeau et al., 2001) , including 2 small (50 CRSs), 2 medium (75 CRSs), 2 large (100 CRSs), and 2 maximum instances (200 CRSs). Two well-known multi-objective algorithms, competitive mechanism based multi-objective particle swarm optimizer (CMOPSO) (Deveci and Güler, 2020) and many-objective evolutionary algorithm based on dominance and decomposition (MOEA/DD) (Tian et al., 2017), were introduced for comparison with the HNSGA-II. All experiments were based on the same system parameters (Li et al., 2022c; Lim et al., 2022). The result evaluation metrics include carbon footprint (E), costs (C), running time (Time) and hypervolume (HV). Where a larger HV value indicates better convergence and distribution of the algorithm (Zitzler and Thiele, 1999).

Table 1 presents the comparative results of the three algorithms (HNSGA-II，CMOPSO，MOEA/DD) solving the instances. From the experimental results in **Table 1**, it can be concluded that the proposed HNSGA-II performs well for test instances with different sizes in solving the MDC-RLPPD. HNSGA-II can obtain higher quality solutions in a shorter time. First, the values of carbon footprint and costs obtained by HNSGA-II are smaller than the results of CMOPSO and MOEA/DD in the eight instances tested. Second, compared with CMOPSO and MOEA/DD, HNSGA-II uses less time when solving instances of different sizes. Third, the HV values obtained by HNSGA-II are greater than those of CMOPSO and MOEA/DD, indicating that HNSGA-II has better comprehensive performance. Fourth, statistical analysis of the results of the two groups (HNSGA-II vs. CMOPSO and HNSGA-II vs. MOEA/DD) shows significant differences between the results, with *p-values* less than 0.05.

3. Results and analysis

To test the model and track the impact of UrS strategy on EPW recycling, Chongqing in southwest China is selected as a case region. Strengthening the recycling and utilization of renewable resources is one of the development guidelines to build a green low-carbon circular economy system in Chongqing (CMPG, 2021). In 2021, the volume of express business in Chongqing increased by 34%. It is of great significance to explore the new mode of EPW recycling to achieve green development. Chongqing, as a national pilot project city for the green transformation of express packaging in China, is steadily promoting the construction of a "waste-free city". It is proposed that the application scale of recyclable express packaging will reach 100,000 by 2025 and a long-term mechanism of governance will be formed throughout the whole chain of express packaging production, use, recycling and disposal (CDRC, 2021). Therefore, it is representative to choose Chongqing as the research object. The benefits $\left(P \text{ and } AE\right)$ in the options are indicated by negative values. The case information is listed in **Table S1** of the Supplementary Material.

3.1 Effects on cost-benefit

Fig. 5 presents the costs and benefits of the three different options for EPW treatment. The results show that the net costs of Option3 is 47.68% less than Option1 and 36.07% less than Option2, which indicates that the application of CSN-EPWR has better economic benefits than the other two options.

In terms of costs, the total costs of Option 3 are 31.67% lower than that of Option 1 and 29.99% lower than that of Option 2. Compared with Option 1, Option 3 has an increase in EPW collection costs (C_1) and a significant decrease in EPW recycling costs (C_2). Since EPW sorting and treatment requires the operation of RC, the increase in C_1 mainly comes from the operating costs of RC. The costs of the additional RC are exchanged for the reduction of intermediate links used to handle MSW, such as waste recycling stations and waste transfer centers. Therefore, the C_2 of Option 3 is 92.88% lower than that of Option 1. Compared with Option 2, the benefits of service collaboration are obvious in Option 3. The C_1 in Option 3 is reduced by 31.45%. The EPW in Option 2 is centrally processed by the RC to participate in

UrS activities as in Option 3, thus there is the same C_2 in both options.

From the perspective of benefits, both Options 2 and 3 are solutions based on UrS strategy, and the benefits achieved account for 16.87 % and 24.1 % of the costs, respectively. Option 1 has the benefits from the introduction of RDF technology to utilize MSW power generation, which is only 5% of the total benefits of Option 3. Among the benefits of Option 3, the direct reuse of EPW makes the major contribution with P_{DC} accounting for 56%. This is followed by the benefits of EPW remanufacturing P_{RM} with a share of 24%. The use of RPF technology in Option 3 brings 70% more resource savings than RDF technology. Finally, the participation of EPW in UrS activities for recycling reduces the costs of sanitary landfill treatment, resulting in the landfill treatment benefits of 11% of the total benefits.

3.2 Effects on carbon footprint-benefit

Fig.6 displays the carbon footprint and benefits of the three different options for EPW treatment. It can be seen from **Fig. 6** that the application of the service collaboration and UrS strategy drives Option 3 to show greater carbon footprint reduction potential than Options 1 and 2. The net footprint of Option 3 are 219% less than Option 1 and 298% less than Option 2.

In terms of carbon footprint, Option 3 reduces carbon footprint by 63.23% compared with Option 1 and 65.98% compared with Option 2. The service alliance with collaborative pickup and delivery activities are a major driver of carbon footprint reduction. The carbon footprint from transportation (E_T) of Option 3 are 96.89% less than Option 1 and 96.96% less than Option 2. In addition, the carbon footprint of Option 3 come from the facilities' energy consumption for processing EPW with RC (E_{RC}), remanufacturing plant (E_{RM}), and WTE plant

(E_{IPG}) accounting for 25.23%, 31.91%, and 36.78%, respectively. In addition to E_T, 22.26% of the carbon footprint in Option 1 result from the waste transfer center and 6% from MSW treatment.

From the perspective of carbon footprint benefits, the UrS strategy has a significant contribution to carbon footprint reduction. The carbon footprint benefits of Option 3 are 2.59 times more than its carbon footprint, which is 6.65 times higher than that of Option 1. There are only carbon footprint benefits that brings by the application of RDF technology in Option 1, which accounts for only 19.83 % of its carbon footprint. The carbon footprint benefits of Option 3 consist of the following sub-items: 33.47% from EPW direct reuse (AE_{DC}), 29.60% from EPW remanufacturing (AE_{RM}), 25.60% from RPF replacement of coal (AE_{IPG}), and 11.33% from landfill treatment (AE_L).

3.3 Impact of improving reuse rate

Fig. 7 shows the results of different reuse rates to explore the resource saving and carbon footprint reduction potential of improving the EPW reuse rate (γ_{dc}) in CSN-EPWR. As shown in **Fig. 7(a)**, when γ_{dc} increases from 40% to 80%, the net costs decrease by 13.07%, where the costs reduce by 5.45% and the cost benefits increases by 20.66%. C_2, P_{RM} and P_{IPG} all decrease as γ_{dc} increases. Conversely, the larger γ_{dc} is, the more resources are saved, and the greater the benefit P_{DC}.

It can be seen from **Fig. 7(b)** that the option with high reuse rate shows better carbon footprint reduction potential. When γ_{dc} increases from 40% to 80%, carbon footprint is decreased by 49.41%. In addition, as γ_{dc} increases, AE_{DC} increases by a smaller percentage than decreases in AE_{RM} and AE_{IPG}, ultimately resulting in a 2.36% increase in net footprints. However, such a result does not imply that the environmental performance of CSN-EPWR becomes worse, just that the relative benefits become less attractive. Because carbon footprint can cause irreversible damage to the environment, the actual carbon footprint produced should be the first criterion.

3.4 Impact of different vehicle type

The use of vehicles plays an important role in resource consumption and environmental impact in CSN-EPWR. To investigate the impact of different express vehicle types on costs and carbon footprint in the CSN-EPWR, a sensitivity analysis of vehicle-related parameters was conducted. **Fig. 8** shows the results for the four different vehicle types of ultra-small, small, medium, and large. As shown in **Fig. 8**, the carbon footprint from transportation, the number of vehicles used, and the total vehicle service time all decrease with the increase of vehicle payload and battery capacity (type becomes larger). For example, when the vehicle type used was changed from ultra-small to large, carbon footprint was reduced by 49.1 % and the number of vehicles used was reduced by 78.95 %. However, the larger the vehicle type, the higher the EPW collection costs. The reduction of carbon footprint is at the expense of costs.

4. Discussion

The traditional research on express packaging recycling network (Li et al., 2022b; Wang et al., 2021) mainly focuses on analyzing the distribution network with recyclable express packaging from the field of operational optimization. There is no related research to introduce the theory of urban symbiosis into the study of EPW recycling. Based on the study of industrial symbiosis applied in industrial parks (Dong et al., 2014; Kim et al., 2018), there have been some detailed evaluation results on the economic and environmental utility of UrS in MSW management (Geng et al., 2010; Xiao et al., 2022). EPW is not considered as an independent recyclable resource for analysis, but mixed with other MSW (Sun et al., 2018; Xiao and Zhou, 2020). In order to better apply UrS theory to the study of EPW recycling optimization, this paper designs an EPW recycling system to explore the resource conservation and carbon footprint reduction potential of the UrS strategy in the EPW recycling network. From the perspective of theoretical research, this study combines the research methods of urban symbiosis and operational optimization, which is hoping to enrich the cross-theoretical discussion between different fields.

EPW recycling is an effective way to address the resource and environmental challenges caused by massive EPW. The results of this study clearly indicate that optimizing EPW recycling network can significantly improve the economic and environmental benefits of EPW management. In addition, the case study in this paper indicates that compared with no cooperation, express companies formed a service alliance to collaborate on express parcels delivery and EPW pickup activities saved 31.45% of costs and 96.96% of carbon footprint. An EPW management system based on the UrS strategy helps to reduce the resource and environmental negative impacts of EPW at the source. The 24.1 % of resource conservation and 2.59 times more carbon footprint reduction benefits than carbon footprint was achieved in the case of this study by introducing the UrS strategy to treat EPW in three ways: reuse, recycling, and replacing.

Based on the findings of this paper, there are some referenceable insights can be provided for stakeholders such as government, express companies and consumers.

Government and industry associations play a significant role in promoting the circular economy of express packaging recycling. From the perspective of the government or industry associations, business cooperation among express companies in last-mile logistics should be encouraged, and the industry should be guided to apply UrS strategy in EPW recycling. Industry standards for EPW classification should also be developed. In addition, carbon taxes and carbon quota systems have been the common way for governments to manage corporate carbon footprint (Carl and Fedor, 2016; Huang et al., 2020). It is a forward-looking policy direction to use the carbon footprint reduction potential realized from participation in UrS activities as an effective mechanism for express companies to reduce carbon taxes or increase carbon quotas. Such policies achieve the carbon footprint reduction target while helping to improve the motivation of express companies to participate in EPW recycling.

Exploring a new model of EPW recycling can enable express companies to maintain sustainable competitiveness in the green and low-carbon development trend. Currently, the recycling system for EPW is immature and incomplete, and there is a lack of infrastructure dedicated to processing EPW. The experimental results in this study show that while the operation of RC in CSN-EPWR increases costs and carbon footprint by a certain amount, the costs and carbon footprint resulting from the treatment of EPW mixed with MSW are more avoided. In the short term, these actions may increase costs of express delivery companies.

However, in the long term, corporate social responsibility may provide a comparative advantage in a competitive market (Duan et al., 2019). In addition, with the development of clean energy technology, material recycling will take precedence over energy recovery in technology comparisons. In a BAU scenario, the potential savings from mixing EPW into MSW incineration will become less attractive, which highlights the significance of building EPW recycling networks. Active service cooperation can be carried out between express companies to accelerate the upgrading and transformation of business. Stable cooperative relationships are maintained by clarifying the responsibilities and benefits distribution related to cooperative business.

As the final node of express parcels and the starting node of EPW, consumers play a key role in the recycling work of EPW. The experimental results show that enhancing the EPW reuse rate in CSN-EPWR is an effective measure to reduce costs and carbon footprint. Therefore, what needs to be highlighted is to improve consumers' awareness of environmental protection to actively participate in EPW recycling. It is necessary to guide residents to dismantle express packaging at community express stations and avoid violent dismantling by building infrastructure and setting up incentives, thereby bringing the benefits of increasing the reuse rate of EPW at the source.

5. Conclusions

This study designed the CSN-EPWR based on the UrS strategy, and the economic and environmental benefits of the network were evaluated by combining material flow analysis and cost-benefit analysis. To plan feasible solution for CSN-EPWR, an optimization model for the MDC-RLPPD and a hybrid heuristic algorithm based on NSGA-II were proposed. Experimental results of several instances show that the designed hybrid heuristic algorithm is an effective method to solve the proposed mathematical model. And a real-world case study indicates that the designed CSN-EPWR has positive implications for resource saving and carbon footprint reduction. In terms of resource saving, the net costs of CSN-EPWR were 47.68% less than Option 1 and 36.07% less than Option 2. From the perspective of carbon footprint reduction, the net footprint of CSN-EPWR were 219% less than Option 1 and 298% less than Option 2. Moreover, the sensitivity analysis of EPW reuse rate shows that the solution with high reuse rate is the pursued goal, and the sensitivity analysis of vehicle type indicates that the use of vehicles with large capacity and high endurance can reduce carbon footprint, but bear additional vehicle costs.

In short, this study provides a comprehensive framework and methodological system to understand the benefits and performance of optimizing the EPW recycling network, and offers implications for the promotion of UrS strategy to help cities achieve green governance and express companies toward sustainable development. In the future, the government or industry associations can promote the circular economy development of express packaging recycling by encouraging enterprise cooperation, guiding model innovation, developing industry standards, building infrastructure and other measures. Express companies can form service alliances to explore new models of express packaging recycling and build EPW recycling network to promote EPW centralized processing. The improvement of consumers' environmental awareness is the key to increasing EPW reuse rate. A circular symbiosis network for EPW recycling constructed in conjunction with UrS strategy is a useful way to solve resource waste and environmental problems in the express delivery industry.

It is worth mentioning that the proposed mathematical model is general and can be used for the design of EPW recycling networks in other regions. This study explores the application of UrS strategy in EPW recycling optimization, which still has some limitations as it is an exploratory attempt between two fields. Due to the availability of data sources, this study only divides express packaging into two categories: plastic and paper. In future research, the classification of express packaging can be further refined. In addition, because the benefits brought by the application of service alliance and UrS strategy may reversely affect the unit costs in the system, the reverse impact of the introduction of UrS strategy on the economic price in the EPW recycling system is also an interesting topic.

CRediT authorship contribution statement

Yuhe Shi: Conceptualization, Methodology, Software, Writing - Original Draft, Formal analysis, Writing - Review & Editing. **Yun Lin:** Resources, Supervision, Funding acquisition, Writing - Review & Editing. **Songyi Wang:** Methodology, Software, Visualization. **Haolin Wen:** Conceptualization, Visualization, Software. **Ming K. Lim:** Methodology, Validation, Writing - Review & Editing. **Ming-Lang Tseng:** Validation, Writing - Review & Editing.

Acknowledgments

This work was supported by the Chinese National Funding of Social Science (grant number 18BJY066); the Fundamental Research Funds for the Central Universities (grant number 2021CDJSKJC14); Chongqing Technology Innovation and Application Development

Special Project (grant number cstc2021jscx-gksbX0069).

Appendix A. Supplementary material

References

Basso, R., Kulcsár, B., Egardt, B., Lindroth, P., Sanchez-Diaz, I., 2019. Energy consumption estimation integrated into the Electric Vehicle Routing Problem. Transportation Research Part D: Transport and Environment 69, 141-167. https://doi.org/10.1016/j.trd.2019.01.006

Bektaş, T., Laporte, G., 2011. The Pollution-Routing Problem. Transportation Research Part B: Methodological 45(8), 1232-1250. https://doi.org/10.1016/j.trb.2011.02.004

Cai, K., Xie, Y., Song, Q., Sheng, N., Wen, Z., 2021. Identifying the status and differences between urban and rural residents' behaviors and attitudes toward express packaging waste management in Guangdong Province, China. Science of The Total Environment 797, 148996. https://doi.org/10.1016/j.scitotenv.2021.148996

Carl, J., Fedor, D., 2016. Tracking global carbon revenues: A survey of carbon taxes versus cap-and-trade in the real world. Energy Policy 96, 50-77. https://doi.org/10.1016/j.enpol.2016.05.023

CDRC, 2021. Suggestions on accelerating the green transformation of express packaging in Chongqing. Chongqing Development and Reform Commission. http://fzggw.cq.gov.cn/zwxx/tzgg/202111/t20211102_9915113.html

Chaabane, A., Montecinos, J., Ouhimmou, M., Khabou, A., 2021. Vehicle routing problem for reverse logistics of End-of-Life Vehicles (ELVs). Waste Management 120, 209-220. https://doi.org/10.1016/j.wasman.2020.11.008

Chaker, M., Berezowska-Azzag, E., Perrotti, D., 2021. Exploring the performances of urban local symbiosis strategy in Algiers, between a potential of energy use optimization and CO2 emissions mitigation. Journal of Cleaner Production 292, 125850. https://doi.org/10.1016/j.jclepro.2021.125850

Chen, X., Fujita, T., Ohnishi, S., Fujii, M., Geng, Y., 2012. The Impact of Scale, Recycling Boundary, and Type of Waste on Symbiosis and Recycling. Journal of Industrial Ecology 16(1), 129-141. https://doi.org/10.1111/j.1530-9290.2011.00422.x

Chertow, M.R., 2007. "Uncovering" Industrial Symbiosis. Journal of Industrial Ecology 11(1), 11-30. https://doi.org/10.1162/jiec.2007.1110

CMPG, 2021. Implementation Opinions on Accelerating the Establishment and Improvement of a Green Low-Carbon Circular Economy System. Chongqing Municipal People's Government. http://www.cq.gov.cn/zwgk/zfxxgkml/zcjd_120614/bmjd/202111/t20211101_9909982.html

Colpo, I., Martins, M.E.S., Buzuku, S., Sellitto, M.A., 2022. Industrial symbiosis in Brazil: A systematic literature review. Waste Management & Research 40(10), 1462-1479. https://doi.org/10.1177/0734242X221084065

Cordeau, J.F., Laporte, G., Mercier, A., 2001. A unified tabu search heuristic for vehicle routing problems with time windows. Journal of the Operational Research Society 52(8), 928-936. https://doi.org/10.1057/palgrave.jors.2601163

Deb, K., Pratap, A., Agarwal, S., Meyarivan, T., 2002. A fast and elitist multiobjective genetic algorithm: NSGA-II. IEEE Transactions on Evolutionary Computation 6(2), 182-197. https://doi.org/10.1109/4235.996017

Deveci, K., Güler, Ö., 2020. A CMOPSO based multi-objective optimization of renewable energy planning: Case of Turkey. Renewable Energy 155, 578-590. https://doi.org/10.1016/j.renene.2020.03.033

Dong, F., Hua, Y., 2018. Are Chinese Residents Willing to Recycle Express Packaging Waste? Evidence from a Bayesian Regularized Neural Network Model. Sustainability 10(11), 4152. https://doi.org/10.3390/su10114152

Dong, H., Geng, Y., Yu, X., Li, J., 2018. Uncovering energy saving and carbon reduction potential from recycling wastes: A case of Shanghai in China. Journal of Cleaner Production 205, 27-35. https://doi.org/10.1016/j.jclepro.2018.08.343

Dong, H., Ohnishi, S., Fujita, T., Geng, Y., Fujii, M., Dong, L., 2014. Achieving carbon emission reduction through industrial & urban symbiosis: A case of Kawasaki. Energy 64, 277-286. https://doi.org/10.1016/j.energy.2013.11.005

Dong, L., Fujita, T., Dai, M., Geng, Y., Ren, J., Fujii, M., Wang, Y., Ohnishi, S., 2016. Towards preventative eco-industrial development: an industrial and urban symbiosis case in one typical industrial city in China. Journal of Cleaner Production 114, 387-400. https://doi.org/10.1016/j.jclepro.2015.05.015

Dong, L., Liang, H., Zhang, L., Liu, Z., Gao, Z., Hu, M., 2017. Highlighting regional eco-industrial development: Life cycle benefits of an urban industrial symbiosis and implications in China. Ecological Modelling 361, 164-176. https://doi.org/10.1016/j.ecolmodel.2017.07.032

Duan, H., Song, G., Qu, S., Dong, X., Xu, M., 2019. Post-consumer packaging waste from express delivery in China. Resources, Conservation and Recycling 144, 137-143. https://doi.org/10.1016/j.resconrec.2019.01.037

Fan, W., Xu, M., Dong, X., Wei, H., 2017. Considerable environmental impact of the rapid development of China's express delivery industry. Resources, Conservation and Recycling 126, 174-176. https://doi.org/10.1016/j.resconrec.2017.07.041

Geng, Y., Tsuyoshi, F., Chen, X., 2010. Evaluation of innovative municipal solid waste management through urban symbiosis: a case study of Kawasaki. Journal of Cleaner Production 18(10), 993-1000. https://doi.org/10.1016/j.jclepro.2010.03.003

Guo, Y., Luo, G., Hou, G., 2021. Research on the Evolution of the Express Packaging Recycling Strategy, Considering Government Subsidies and Synergy Benefits. International Journal of Environmental Research and Public Health 18(3), 1144. https://doi.org/10.3390/ijerph18031144

Hannan, M.A., Akhtar, M., Begum, R.A., Basri, H., Hussain, A., Scavino, E., 2018. Capacitated vehicle-routing problem model for scheduled solid waste collection and route optimization using PSO algorithm. Waste Management 71, 31-41. https://doi.org/10.1016/j.wasman.2017.10.019

Hannan, M.A., Begum, R.A., Al-Shetwi, A.Q., Ker, P.J., Al Mamun, M.A., Hussain, A., Basri, H., Mahlia, T.M.I., 2020. Waste collection route optimisation model for linking cost saving and emission reduction to achieve sustainable development goals. Sustainable Cities and Society 62, 102393. https://doi.org/10.1016/j.scs.2020.102393

Hua, Y., Dong, F., Goodman, J., 2021. How to leverage the role of social capital in pro-environmental behavior: A case study of residents' express waste recycling behavior in China. Journal of Cleaner Production 280, 124376. https://doi.org/10.1016/j.jclepro.2020.124376

Huang, Y.-S., Fang, C.-C., Lin, Y.-A., 2020. Inventory management in supply chains with consideration of Logistics, green investment and different carbon emissions policies. Computers

& Industrial Engineering 139, 106207. https://doi.org/10.1016/j.cie.2019.106207

Huo, T., Xu, L., Feng, W., Cai, W., Liu, B., 2021. Dynamic scenario simulations of carbon emission peak in China's city-scale urban residential building sector through 2050. Energy Policy 159, 112612. https://doi.org/10.1016/j.enpol.2021.112612

Kang, P., Song, G., Xu, M., Miller, T.R., Wang, H., Zhang, H., Liu, G., Zhou, Y., Ren, J., Zhong, R., Duan, H., 2021. Low-carbon pathways for the booming express delivery sector in China. Nature Communications 12, 450. https://doi.org/10.1038/s41467-020-20738-4

Kim, H.-W., Dong, L., Choi, A.E.S., Fujii, M., Fujita, T., Park, H.-S., 2018. Co-benefit potential of industrial and urban symbiosis using waste heat from industrial park in Ulsan, Korea. Resources, Conservation and Recycling 135, 225-234. https://doi.org/10.1016/j.resconrec.2017.09.027

Lenhart, J., van Vliet, B., Mol, A.P.J., 2015. New roles for local authorities in a time of climate change: the Rotterdam Energy Approach and Planning as a case of urban symbiosis. Journal of Cleaner Production 107, 593-601. https://doi.org/10.1016/j.jclepro.2015.05.026

Li, J., Song, G., Cai, M., Bian, J., Sani Mohammed, B., 2022a. Green environment and circular economy: A state-of-the-art analysis. Sustainable Energy Technologies and Assessments 52, 102106. https://doi.org/10.1016/j.seta.2022.102106

Li, R., He, M., He, H., Deng, Q., 2022b. Heuristic column generation for designing an express circular packaging distribution network. Operational Research 22(2), 1103-1126. https://doi.org/10.1007/s12351-020-00570-w

Li, Y., Lim, M.K., Wang, C., 2022c. An intelligent model of green urban distribution in the blockchain environment. Resources, Conservation and Recycling 176, 105925.

https://doi.org/10.1016/j.resconrec.2021.105925

Lim, M.K., Li, Y., Wang, C., Tseng, M.-L., 2022. Prediction of cold chain logistics temperature using a novel hybrid model based on the mayfly algorithm and extreme learning machine. Industrial Management & Data Systems 122(3), 819-840. https://doi.org/10.1108/IMDS-10-2021-0607

Longo, S., Cellura, M., Girardi, P., 2020. Life Cycle Assessment of electricity production from refuse derived fuel: A case study in Italy. Science of The Total Environment 738, 139719. https://doi.org/10.1016/j.scitotenv.2020.139719

Lu, C., Wang, S., Wang, K., Gao, Y., Zhang, R., 2020. Uncovering the benefits of integrating industrial symbiosis and urban symbiosis targeting a resource-dependent city: A case study of Yongcheng, China. Journal of Cleaner Production 255, 120210. https://doi.org/10.1016/j.jclepro.2020.120210

Ma, Y., Zhang, W., Feng, C., Lev, B., Li, Z., 2021. A bi-level multi-objective location-routing model for municipal waste management with obnoxious effects. Waste Management 135, 109-121. https://doi.org/10.1016/j.wasman.2021.08.034

Maskooki, A., Deb, K., Kallio, M., 2022. A customized genetic algorithm for bi-objective routing in a dynamic network. European Journal of Operational Research 297(2), 615-629. https://doi.org/10.1016/j.ejor.2021.05.018

Ohnishi, S., Dong, H., Geng, Y., Fujii, M., Fujita, T., 2017. A comprehensive evaluation on industrial & urban symbiosis by combining MFA, carbon footprint and emergy methods—Case of Kawasaki, Japan. Ecological Indicators 73, 513-524. https://doi.org/10.1016/j.ecolind.2016.10.016

Rabbani, M., Farrokhi-Asl, H., Asgarian, B., 2017. Solving a bi-objective location routing problem by a NSGA-II combined with clustering approach: application in waste collection problem. Journal of

Industrial Engineering International 13(1), 13-27. https://doi.org/10.1007/s40092-016-0172-8

Rubio, S., Ramos, T.R.P., Leitão, M.M.R., Barbosa-Povoa, A.P., 2019. Effectiveness of extended producer responsibility policies implementation: The case of Portuguese and Spanish packaging waste systems. Journal of Cleaner Production 210, 217-230. https://doi.org/10.1016/j.jclepro.2018.10.299

Sellitto, M.A., Murakami, F.K., Butturi, M.A., Marinelli, S., Kadel Jr, N., Rimini, B., 2021. Barriers, drivers, and relationships in industrial symbiosis of a network of Brazilian manufacturing companies. Sustainable Production and Consumption 26, 443-454. https://doi.org/10.1016/j.spc.2020.09.016

Shi, Y., Lin, Y., Li, B., Yi Man Li, R., 2022a. A bi-objective optimization model for the medical supplies' simultaneous pickup and delivery with drones. Computers & Industrial Engineering 171, 108389. https://doi.org/10.1016/j.cie.2022.108389

Shi, Y., Lin, Y., Lim, M.K., Tseng, M.-L., Tan, C., Li, Y., 2022b. An intelligent green scheduling system for sustainable cold chain logistics. Expert Systems with Applications 209, 118378. https://doi.org/10.1016/j.eswa.2022.118378

Siddiqi, A., Haraguchi, M., Narayanamurti, V., 2020. Urban waste to energy recovery assessment simulations for developing countries. World Development 131, 104949. https://doi.org/10.1016/j.worlddev.2020.104949

Song, J., Feng, R., Yue, C., Shao, Y., Han, J., Xing, J., Yang, W., 2022a. Reinforced urban waste management for resource, energy and environmental benefits: China's regional potentials. Resources, Conservation and Recycling 178, 106083. https://doi.org/10.1016/j.resconrec.2021.106083

Song, Z., Xiu, F.-R., Qi, Y., 2022b. Degradation and partial oxidation of waste plastic express packaging bags in supercritical water: Resources transformation and pollutants removal. Journal of Hazardous Materials 423, 127018. https://doi.org/10.1016/j.jhazmat.2021.127018

Su, Y., Duan, H., Wang, Z., Song, G., Kang, P., Chen, D., 2020. Characterizing the environmental impact of packaging materials for express delivery via life cycle assessment. Journal of Cleaner Production 274, 122961. https://doi.org/10.1016/j.jclepro.2020.122961

Sun, L., Fujii, M., Tasaki, T., Dong, H., Ohnishi, S., 2018. Improving waste to energy rate by promoting an integrated municipal solid-waste management system. Resources, Conservation and Recycling 136, 289-296. https://doi.org/10.1016/j.resconrec.2018.05.005

Sun, L., Li, H., Dong, L., Fang, K., Ren, J., Geng, Y., Fujii, M., Zhang, W., Zhang, N., Liu, Z., 2017. Eco-benefits assessment on urban industrial symbiosis based on material flows analysis and emergy evaluation approach: A case of Liuzhou city, China. Resources, Conservation and Recycling 119, 78-88. https://doi.org/10.1016/j.resconrec.2016.06.007

Tian, Y., Cheng, R., Zhang, X., Jin, Y., 2017. PlatEMO: A MATLAB Platform for Evolutionary Multi-Objective Optimization [Educational Forum]. IEEE Computational Intelligence Magazine 12(4), 73-87. https://doi.org/10.1109/MCI.2017.2742868

Van Berkel, R., Fujita, T., Hashimoto, S., Geng, Y., 2009. Industrial and urban symbiosis in Japan: Analysis of the Eco-Town program 1997–2006. Journal of Environmental Management 90(3), 1544-1556. https://doi.org/10.1016/j.jenvman.2008.11.010

Wang, Y., Peng, S., Guan, X., Fan, J., Wang, Z., Liu, Y., Wang, H., 2021. Collaborative logistics pickup and delivery problem with eco-packages based on time–space network. Expert Systems with Applications 170, 114561. https://doi.org/10.1016/j.eswa.2021.114561

Wen, Z., Xie, Y., Chen, M., Dinga, C.D., 2021. China’s plastic import ban increases prospects of environmental impact mitigation of plastic waste trade flow worldwide. Nature Communications 12(1), 425. https://doi.org/10.1038/s41467-020-20741-9

Xiao, L., Fan, R., Wang, C., Wang, J., 2020. Policy Analyses on Promoting the Recycling of Express Packages. Sustainability 12(22), 9504. https://doi.org/10.3390/su12229504

Xiao, S., Dong, H., Geng, Y., Tian, X., 2022. Low carbon potential of urban symbiosis under different municipal solid waste sorting modes based on a system dynamic method. Resources, Conservation and Recycling 179, 106108. https://doi.org/10.1016/j.resconrec.2021.106108

Xiao, Y., Zhou, B., 2020. Does the development of delivery industry increase the production of municipal solid waste?—An empirical study of China. Resources, Conservation and Recycling 155, 104577. https://doi.org/10.1016/j.resconrec.2019.104577

Xu, R., Chen, C., Chen, D., Zhou, G., Jin, Y., Wu, X., Wang, W., Feng, X., Liu, S., Lin, Z., 2022. Maximum openable capacity optimization method of active distribution network considering multiple users access. Energy Reports 8, 43-50. https://doi.org/10.1016/j.egyr.2022.02.115

Yadav, A., Mishra, S., Sairam, A.S., 2022. A multi-objective worker selection scheme in crowdsourced platforms using NSGA-II. Expert Systems with Applications 201, 116991. https://doi.org/10.1016/j.eswa.2022.116991

Yang, J., Long, R., Chen, H., 2022. Decision-making dynamic evolution among groups regarding express packaging waste recycling under different reference dependence and information policy. Waste Management 138, 262-273. https://doi.org/10.1016/j.wasman.2021.12.003

Yang, J., Long, R., Chen, H., Sun, Q., 2021. A comparative analysis of express packaging waste recycling models based on the differential game theory. Resources, Conservation and Recycling 168, 105449. https://doi.org/10.1016/j.resconrec.2021.105449

Zhang, S., Gajpal, Y., Appadoo, S.S., Abdulkader, M.M.S., 2018. Electric vehicle routing problem with recharging stations for minimizing energy consumption. International Journal of Production Economics 203, 404-413. https://doi.org/10.1016/j.ijpe.2018.07.016

Zhao, Z., Liu, B., Zhang, C., Liu, H., 2019. An improved adaptive NSGA-II with multi-population algorithm. Applied Intelligence 49, 569-580. https://doi.org/10.1007/s10489-018-1263-6

Zitzler, E., Thiele, L., 1999. Multiobjective evolutionary algorithms: a comparative case study and the strength Pareto approach. IEEE Transactions on Evolutionary Computation 3(4), 257-271. https://doi.org/10.1109/4235.797969

Figures and tables

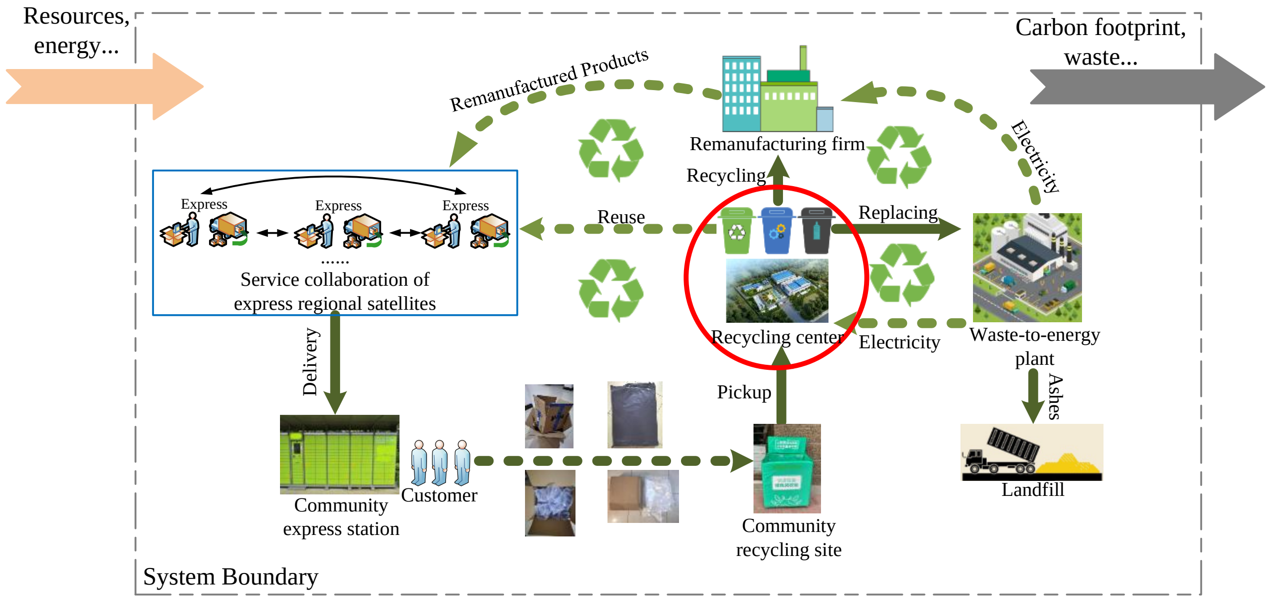


Fig.1. The framework and organization of the circular symbiosis network for EPW recycling.

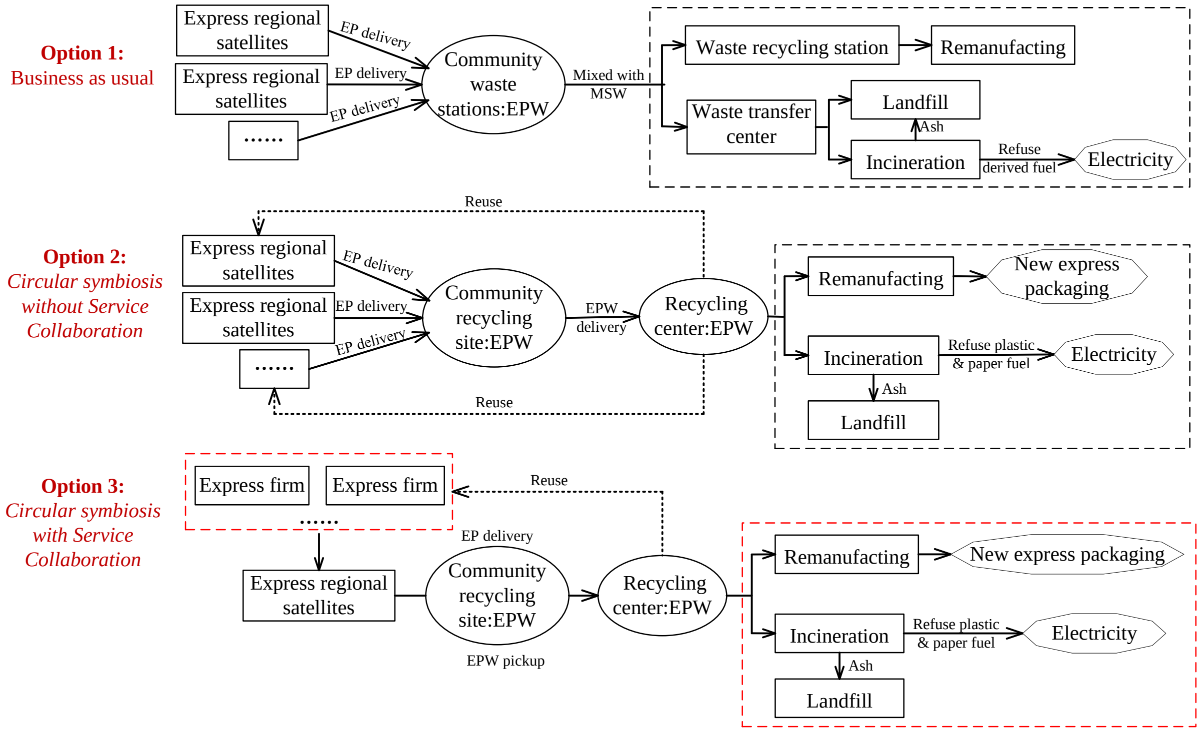
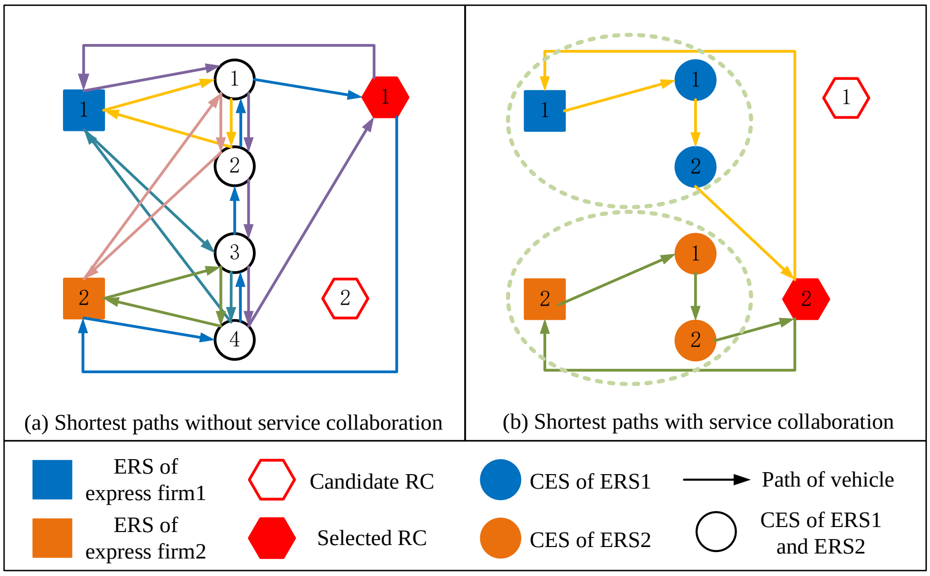


Fig.2. Schematic diagram of three EPW treatment options.



(a) Shortest paths without service collaboration

(b) Shortest paths with service collaboration

Fig.3 Comparison of logistics operations between service collaboration and non-service collaborative.

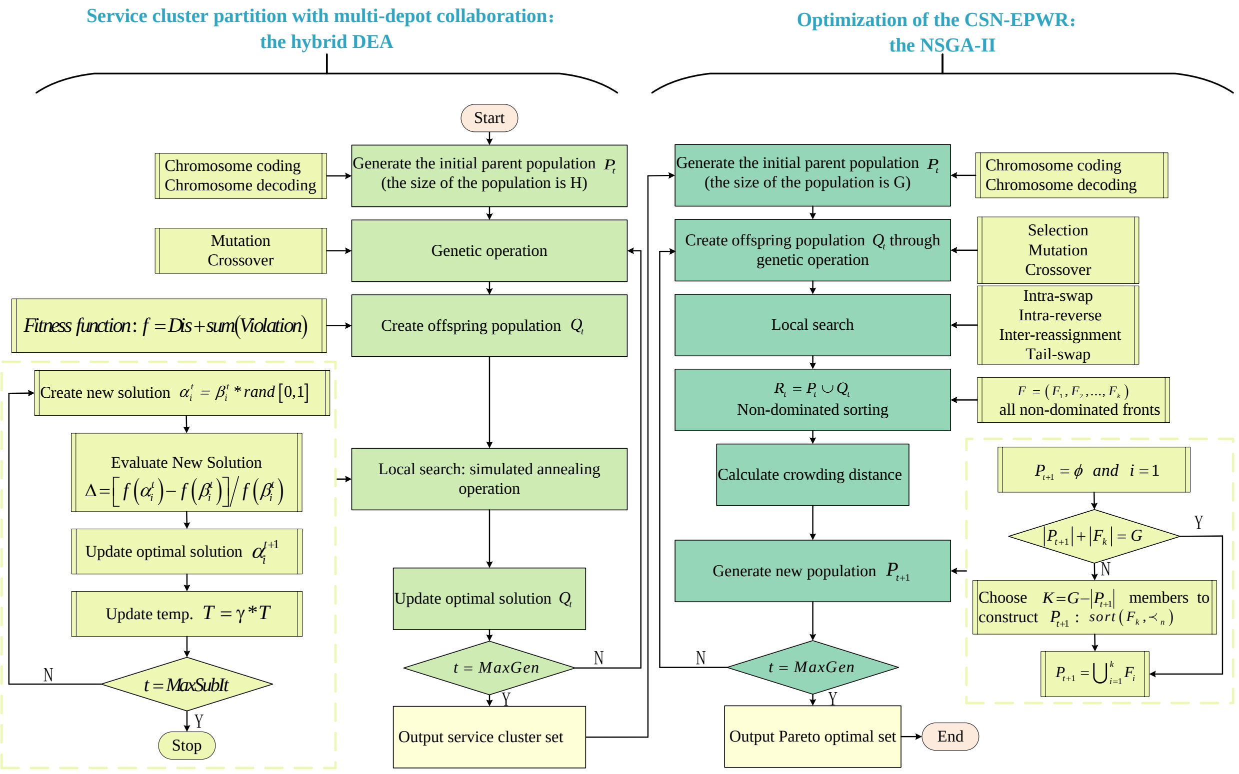


Fig.4 The flowchart of the HNSGA-II.

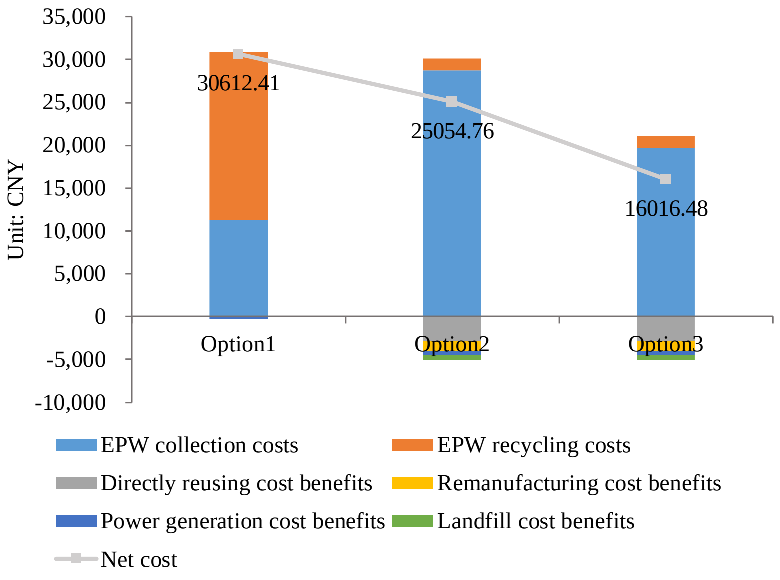


Fig. 5. Costs and benefits of different options for EPW treatment.

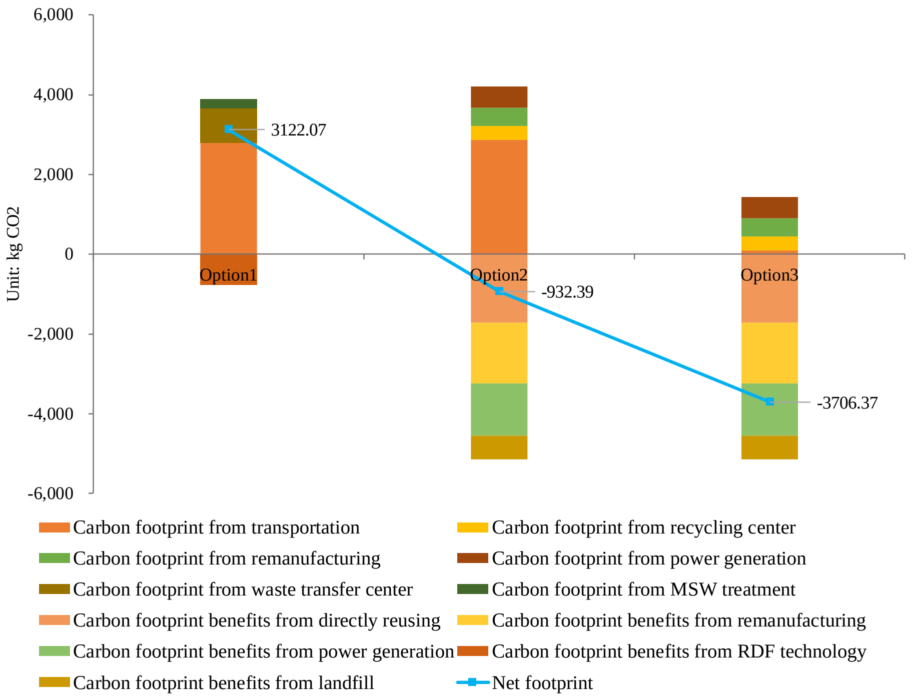
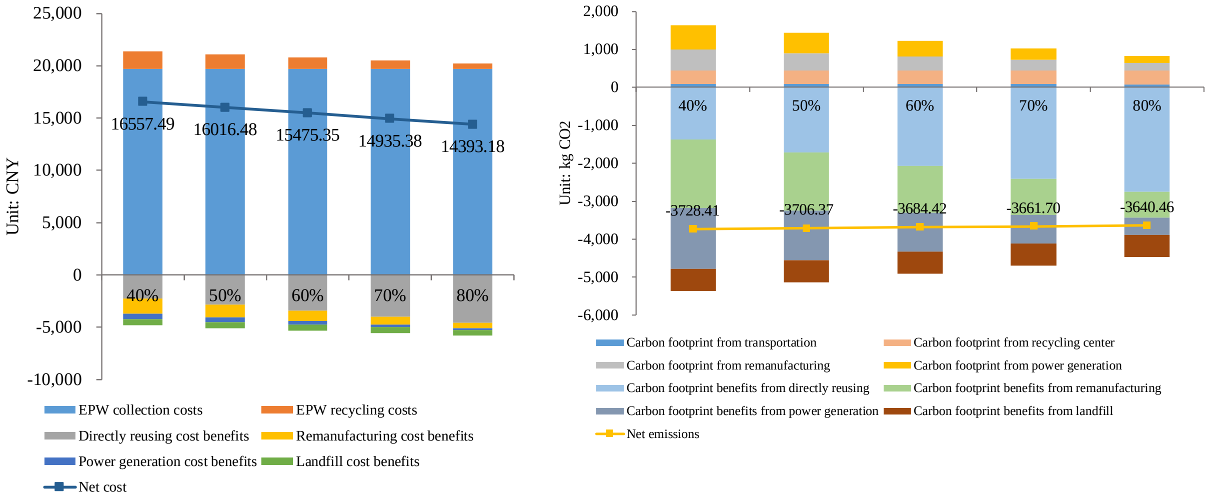


Fig. 6. Carbon footprint and benefits of different options for EPW treatment.



(a) Cost-benefit (b) Carbon footprint-benefit

Fig. 7. Results for different reuse rates.

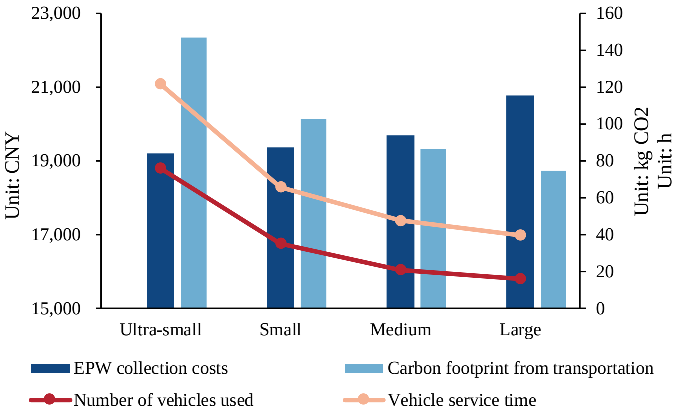


Fig. 8. Results for different vehicle type.

Table 1. Results of different instances using three algorithms.

Instance	HNSGA-II				CMOPSO				MOEA/DD			
	E (kg)	C (¥)	Time(s)	HV	E (kg)	C (¥)	Time(s)	HV	E (kg)	C (¥)	Time(s)	HV
50-1	1293.94	22753.17	119.26	0.5295	1307.47	22763.25	141.07	0.5046	1304.67	22761.16	139.09	0.5056
50-2	1858.55	22179.8	99.63	0.5173	1878.74	22194.85	128.74	0.492	1875.91	22192.74	129.09	0.4928
75-1	1945.5	30539.07	187.11	0.4105	1960.47	30549.91	202.63	0.3874	1956.43	30546.9	209.65	0.3871
75-2	2985.13	30834.84	175.17	0.4573	3009.66	30853.13	215.41	0.4328	3062.53	30892.53	190.34	0.4223
100-1	2277.5	36736.79	233.8	0.4824	2295.49	36750.21	248.87	0.4583	2285.25	36742.57	246.72	0.4606
100-2	3135.89	37328.81	239.09	0.4298	3163.95	37349.72	252.75	0.4047	3151.84	37340.7	273.14	0.4069
200-1	6061.9	66516.16	395.1	0.3877	6103.2	66546.94	410.78	0.3635	6107.71	66550.31	415.46	0.3631
200-2	5902.55	64866.2	477.83	0.4038	5958.72	64908.07	490.5	0.3781	5919.76	64879.03	503.17	0.382
AVG	3182.62	38969.36	240.87	0.4523	3209.71	38989.51	261.34	0.4277	3208.013	38988.24	263.33	0.4276
t-test	-	-	-	-	-5.21	-5.18	-6.00	84.88	-2.98	-2.96	-9.02	16.35
p-value	-	-	-	-	1.24E-03	1.28E-03	5.41E-04	8.30E-12	2.06E-02	2.10E-02	4.20E-05	7.79E-07